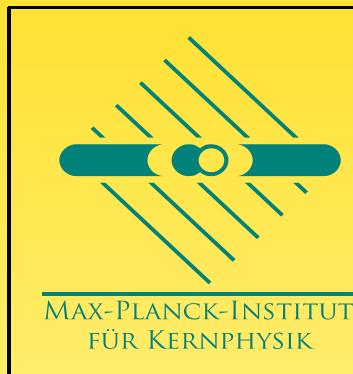
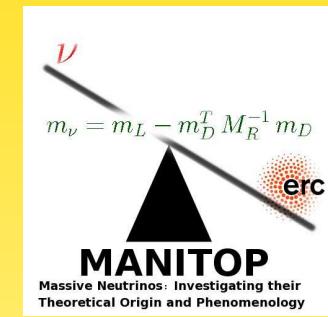


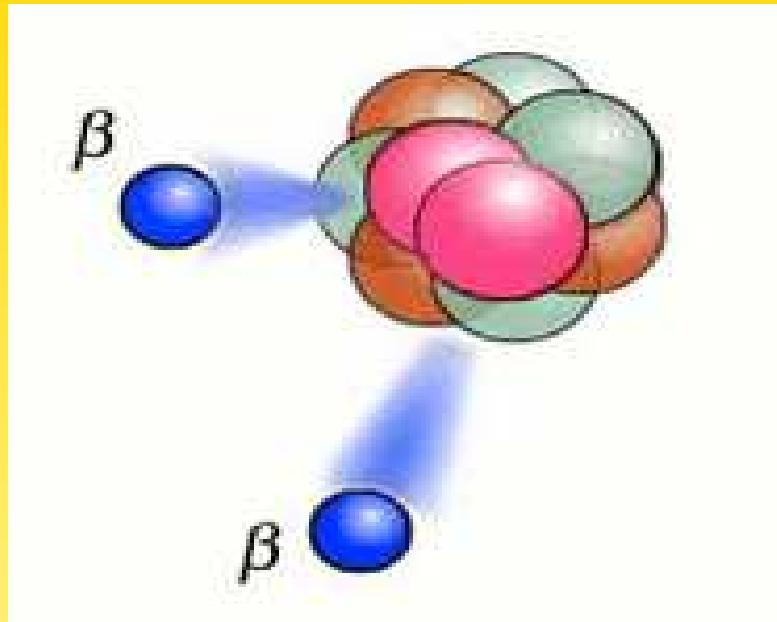
The Origin of Neutrino Masses and Neutrinoless Double Beta Decay



WERNER RODEJOHANN
TAUP 2013
09/09/13



What is Neutrinoless Double Beta Decay?



For example:



VIOLATION OF LEPTON NUMBER!

Standard Model of particle physics: lepton number (accidentally) conserved

Outline

$(A, Z) \rightarrow (A, Z + 2) + 2 e^- \quad (0\nu\beta\beta) \Rightarrow \text{Lepton Number Violation}$

- Introduction
- **Standard Interpretation** (neutrino physics)
- **Non-Standard Interpretations** (BSM \neq neutrino physics)

Why should we probe Lepton Number Violation?

- L and B accidentally conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_{\text{LNV}} + \frac{1}{\Lambda^2} \mathcal{L}_{\text{LFV, BNV, LNV}} + \dots$
- baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majorana neutrinos
- (chiral anomalies: $\partial_\mu J_{B,L}^\mu = c G_{\mu\nu} \tilde{G}^{\mu\nu} \neq 0$ with $J_\mu^B = \sum \bar{q}_i \gamma_\mu q_i$ and $J_\mu^L = \sum \bar{\ell}_i \gamma_\mu \ell_i$)

⇒ Lepton Number Violation as important as Baryon Number Violation
($0\nu\beta\beta$ is much more than a neutrino mass experiment)

Upcoming/running experiments: exciting time!!

best limit was from 2001...

Name	Isotope	source = detector; calorimetric with			source \neq detector
		high energy res.	low energy res.	event topology	
AMoRE	^{100}Mo	✓	—	—	—
CANDLES	^{48}Ca	—	✓	—	—
COBRA	^{116}Cd	—	—	✓	—
CUORE	^{130}Te	✓	—	—	—
DCBA	^{150}Nd	—	—	—	✓
EXO	^{136}Xe	—	—	✓	—
GERDA	^{76}Ge	✓	—	—	—
KamLAND-Zen	^{136}Xe	—	✓	—	—
LUCIFER	^{82}Se	✓	—	—	—
MAJORANA	^{76}Ge	✓	—	—	—
MOON	^{100}Mo	—	—	—	✓
NEXT	^{136}Xe	—	—	✓	—
SNO+	^{130}Te	—	✓	—	—
SuperNEMO	^{82}Se	—	—	—	✓
XMASS	^{136}Xe	—	✓	—	—

Recent reviews. . .

- X. Sarazin, [Review of double beta experiments](#), 1210.7666
- B. Schwingenheuer, [Status and prospects of searches for neutrinoless double beta decay](#), 1210.7432
- W. Rodejohann, [Neutrino-less double beta decay and particle physics](#), 1106.1334
- J.J. Gomez-Cadenas et al., [The search for neutrinoless double beta decay](#), 1109.5515
- J.D. Vergados, H. Ejiri, F. Simkovic, [Theory of neutrinoless double beta decay](#), 1205.0649
- S.M. Bilensky, C. Giunti, [Neutrinoless double-beta decay. A brief review](#), 1203.5250
- S.R. Elliott, [Recent progress in double beta decay](#), 1203.1070
- A. de Gouvea, P. Vogel, [Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model](#), 1303.4097
- S.T Petcov, [The Nature of Massive Neutrinos](#), 1303.5819
- P. Vogel, [Nuclear structure and double beta decay](#), J. Phys. G 39, 124002 (2012)
- S.J. Freeman, J.P. Schiffer, [Constraining the \$0\nu2\beta\$ matrix elements by nuclear structure observables](#), J. Phys. G 39, 124004 (2012)
- J. Suhonen, O. Civitarese, [Review of the properties of the \$0\nu\beta^-\beta^-\$ nuclear matrix elements](#), J. Phys. G 39, 124005 (2012)
- A. Faessler, V. Rodin, F. Simkovic, [Nuclear matrix elements for neutrinoless double beta decay and double electron capture](#), J. Phys. G 39, 124006 (2012)
- F. Deppisch, M. Hirsch, H. Päs, [Neutrinoless double beta decay and physics beyond the standard model](#), J. Phys. G 39, 124007 (2012)
- W. Rodejohann, [Neutrinoless double beta decay and neutrino physics](#), J. Phys. G 39, 124008 (2012)
- K. Zuber, [Double beta decay experiments](#), J. Phys. G 39, 124009 (2012)

Experimental Aspects: existing limits

Isotope	$T_{1/2}^{0\nu}$ [yrs]	Experiment
^{48}Ca	5.8×10^{22}	CANDLES
^{76}Ge	1.9×10^{25}	HDM
	2.1×10^{25}	GERDA
	3.0×10^{25}	GERDA+HDM+IGEX
^{82}Se	3.2×10^{23}	NEMO-3
^{100}Mo	1.0×10^{24}	NEMO-3
^{130}Te	2.8×10^{24}	CUORE
^{136}Xe	1.6×10^{25}	EXO
^{136}Xe	1.9×10^{25}	KamLAND-Zen
^{136}Xe	3.4×10^{25}	EXO+KamLAND-Zen
^{150}Nd	1.8×10^{22}	NEMO-3

Future limits

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking
GERDA	^{76}Ge	18	3×10^{25}	running	~ 2011
		40	2×10^{26}	in progress	~ 2012
		1000	6×10^{27}	R&D	~ 2015
CUORE	^{130}Te	200	$6.5 \times 10^{26}* \\ 2.1 \times 10^{26}**$	in progress	~ 2013
MAJORANA	^{76}Ge	30-60	$(1 - 2) \times 10^{26}$	in progress	~ 2013
		1000	6×10^{27}	R&D	~ 2015
EXO	^{136}Xe	200	6.4×10^{25}	in progress	~ 2011
		1000	8×10^{26}	R&D	~ 2015
SuperNEMO	^{82}Se	100-200	$(1 - 2) \times 10^{26}$	R&D	$\sim 2013\text{-}15$
KamLAND-Zen	^{136}Xe	400	4×10^{26}	in progress	~ 2011
		1000	10^{27}	R&D	$\sim 2013\text{-}15$
SNO+	^{130}Te	800	$\sim 10^{26}$	in progress	~ 2014
		8000	$\sim 10^{27}$	R&D	~ 2017

Experimental Aspects

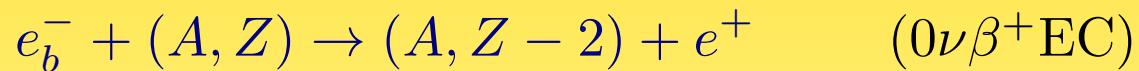
$$(T_{1/2}^{0\nu})^{-1} \propto \begin{cases} a M \varepsilon t & \text{without background} \\ a \varepsilon \sqrt{\frac{M t}{B \Delta E}} & \text{with background} \end{cases}$$

with

- B is background index in counts/(keV kg yr)
- ΔE is energy resolution
- ϵ is efficiency
- $(T_{1/2}^{0\nu})^{-1} \propto (\text{particle physics})^2$

Note: factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

Alternative processes



all depend on the same particle physics parameters, but are more difficult to realize/test

BUT: ratio to $0\nu\beta\beta$ is test of NME calculation and LNV mechanism

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q, Z) |\mathcal{M}_x(A, Z) \eta_x|^2$$

- $G_x(Q, Z)$: phase space factor
- $\mathcal{M}_x(A, Z)$: nuclear physics
- η_x : particle physics

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q, Z) |\mathcal{M}_x(A, Z) \eta_x|^2$$

- $G_x(Q, Z)$: phase space factor; **calculable**
- $\mathcal{M}_x(A, Z)$: nuclear physics; **problematic**
- η_x : particle physics; **interesting**

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q, Z) |\mathcal{M}_x(A, Z) \eta_x|^2$$

- $G_x(Q, Z)$: phase space factor (Kotila, Iachello and Stoica, Mirea)
- $\mathcal{M}_x(A, Z)$: nuclear physics (talk by Fedor Simkovic)
- η_x : particle physics (talks by Deppisch, Meroni, me)

3 Reasons for Multi-isotope determination

- 1.) credibility
- 2.) test NME calculation

$$\frac{T_{1/2}^{0\nu}(A_1, Z_1)}{T_{1/2}^{0\nu}(A_2, Z_2)} = \frac{G(Q_2, Z_2)}{G(Q_1, Z_1)} \frac{|\mathcal{M}(A_2, Z_2)|^2}{|\mathcal{M}(A_1, Z_1)|^2}$$

systematic errors drop out, ratio sensitive to NME model

- 3.) test mechanism

$$\frac{T_{1/2}^{0\nu}(A_1, Z_1)}{T_{1/2}^{0\nu}(A_2, Z_2)} = \frac{G_x(Q_2, Z_2)}{G_x(Q_1, Z_1)} \frac{|\mathcal{M}_x(A_2, Z_2)|^2}{|\mathcal{M}_x(A_1, Z_1)|^2}$$

particle physics drops out, ratio of NMEs sensitive to mechanism

Interpretation of Neutrino-less Double Beta Decay

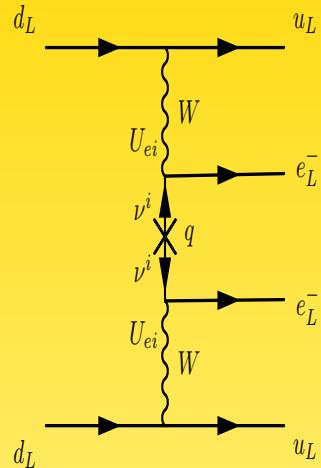
- **Standard Interpretation:**

Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution

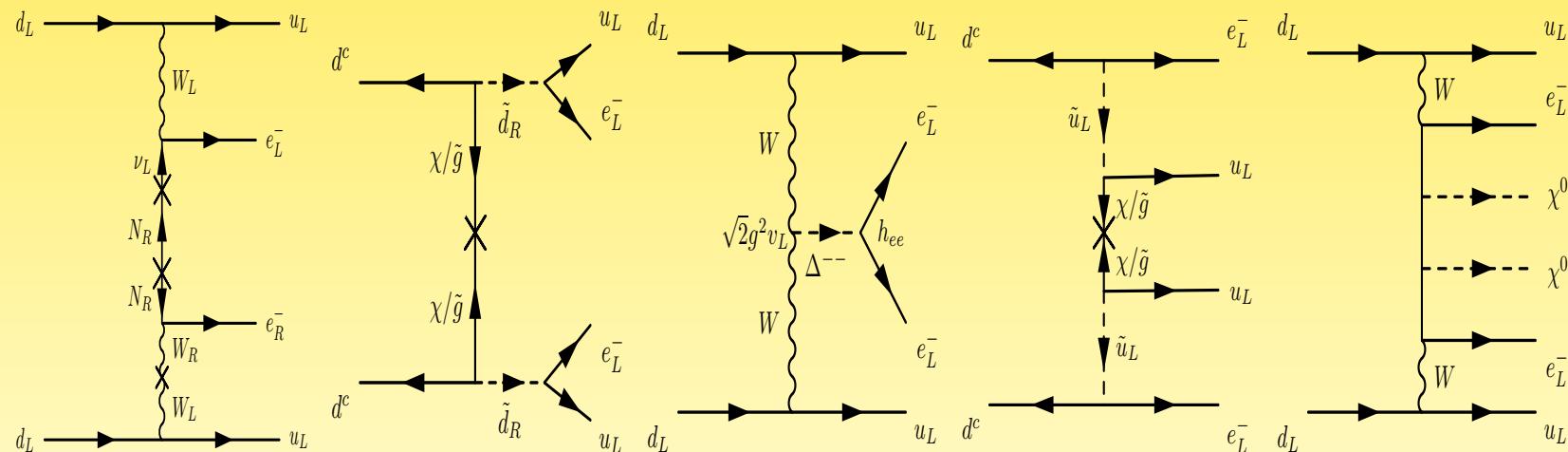
- **Non-Standard Interpretations:**

There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism

- Standard Interpretation:

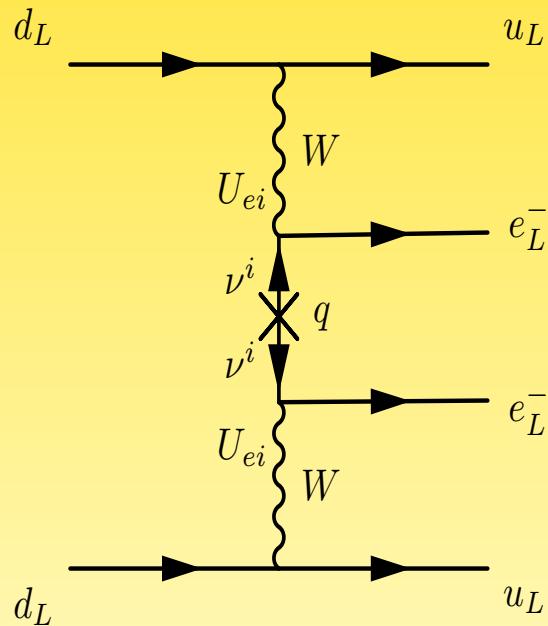


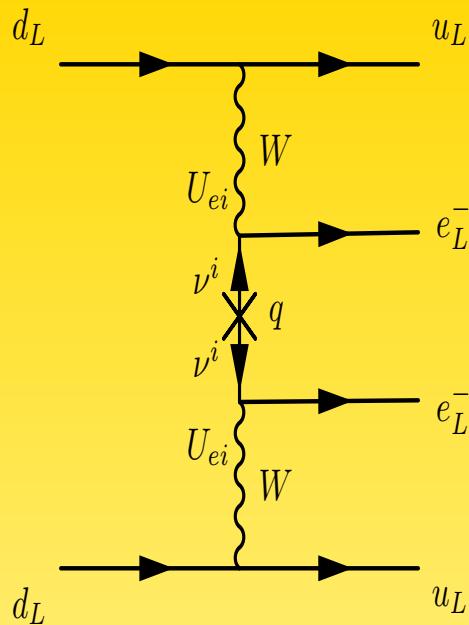
- Non-Standard Interpretations:



Standard Interpretation

Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution





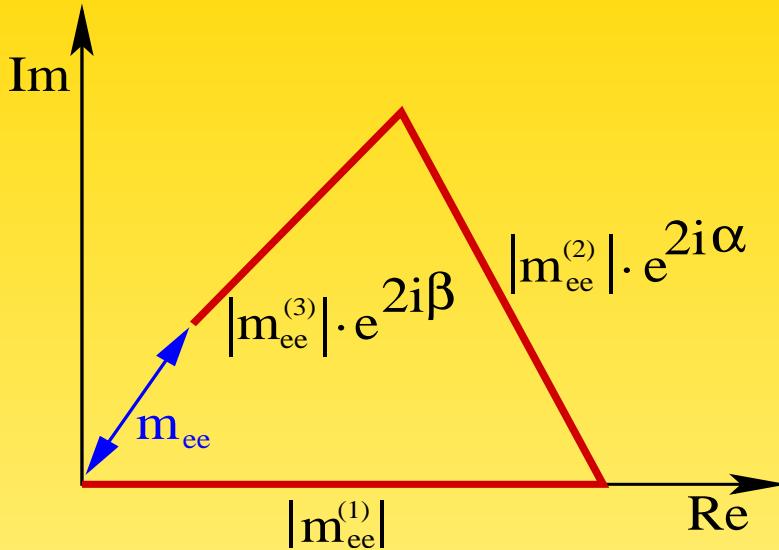
- U_{ei}^2 from charged current
- m_i/E_i from spin-flip and *if neutrinos are Majorana particles*

amplitude proportional to **effective mass**

$$|m_{ee}| = \left| \sum U_{ei}^2 m_i \right|$$

$m/E \simeq \text{eV}/100 \text{ MeV}$ is tiny: only N_A can save the day!

The effective mass



Amplitude proportional to coherent sum (“effective mass”):

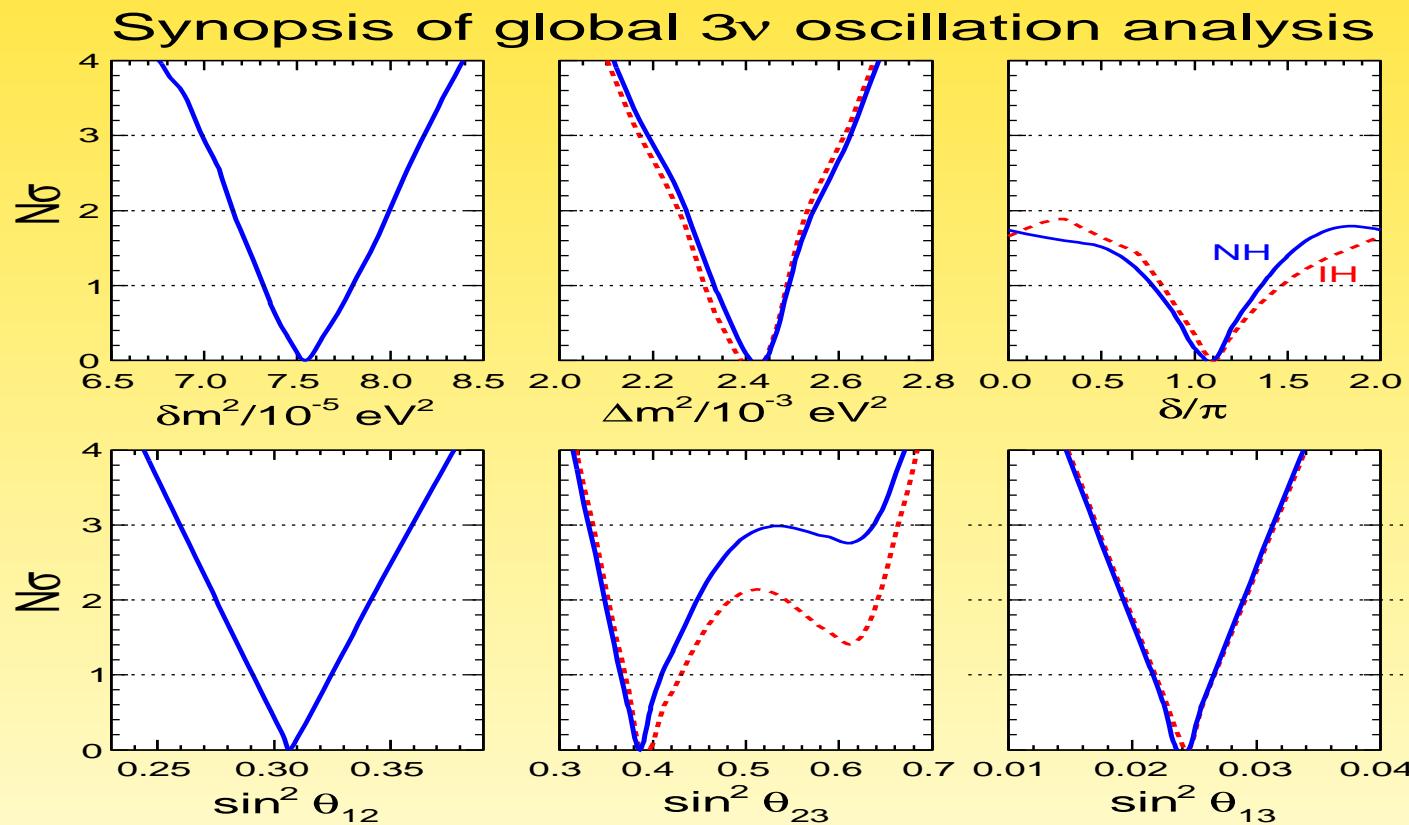
$$|m_{ee}| \equiv \left| \sum U_{ei}^2 m_i \right| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta} \right|$$

$$= f(\theta_{12}, |U_{e3}|, m_i, \text{sgn}(\Delta m_A^2), \alpha, \beta)$$

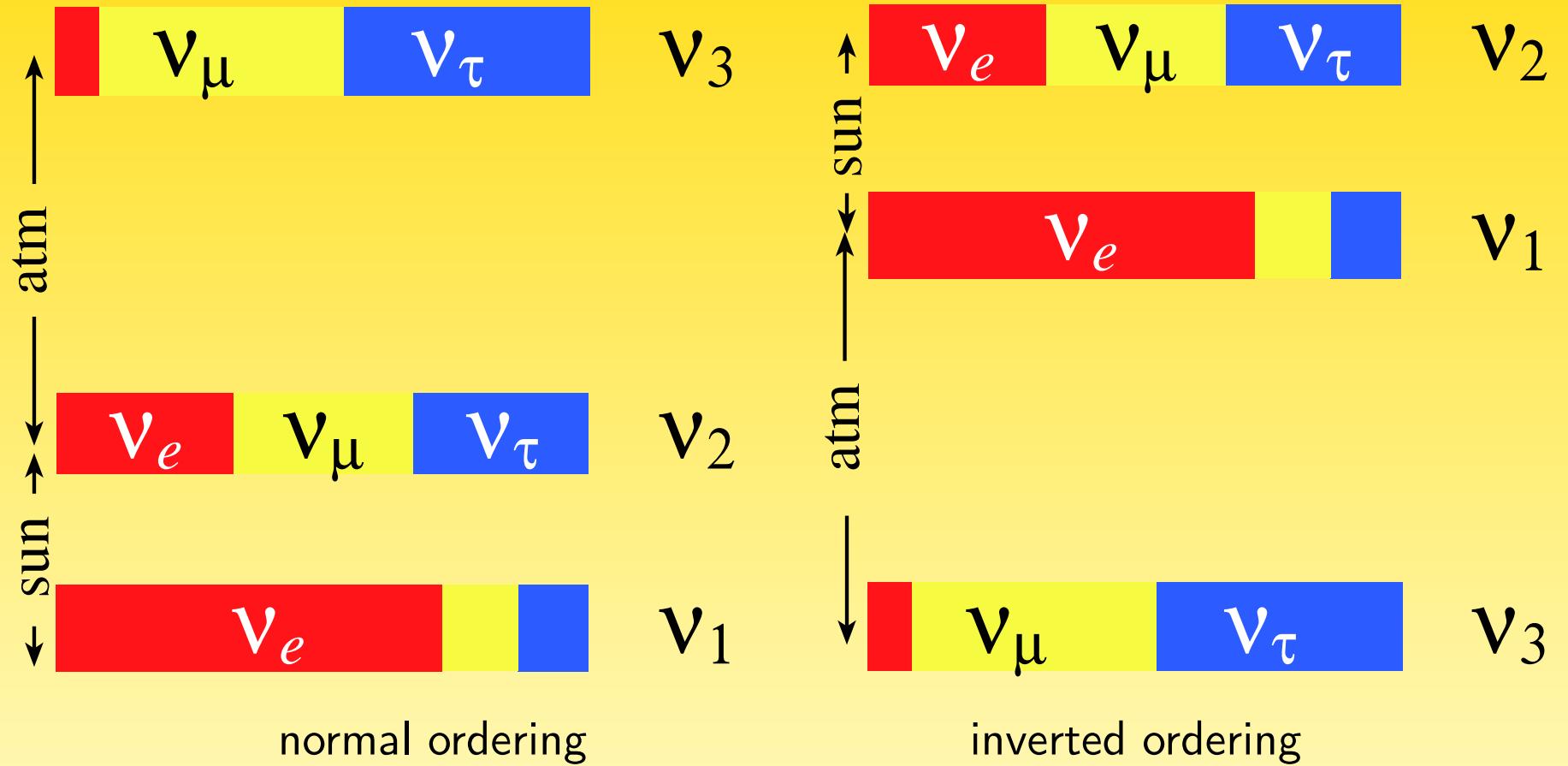
7 out of 9 parameters of neutrino physics!

Insert (known) Neutrino Data

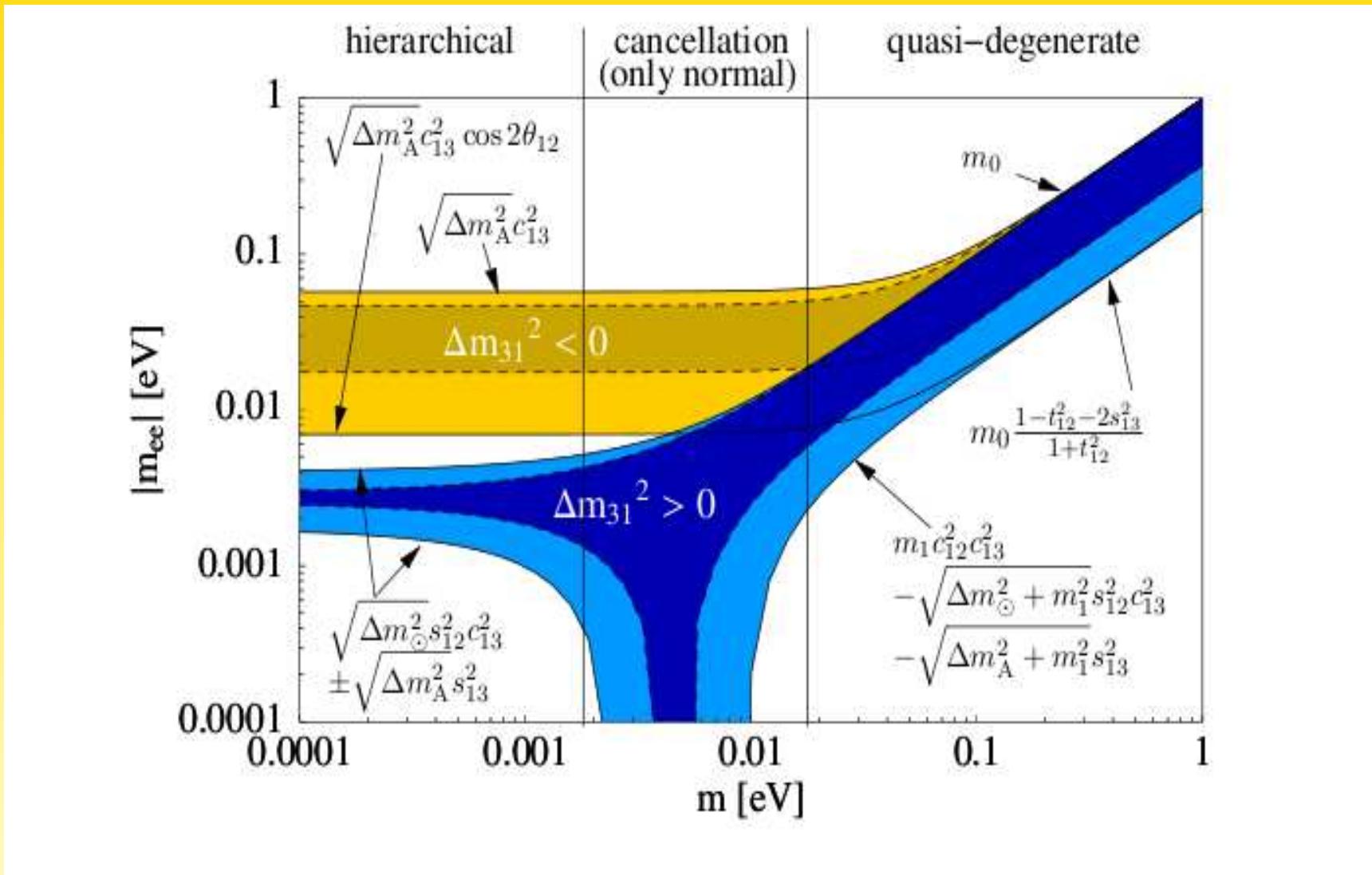
$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} e^{i\alpha} & s_{13} e^{i\beta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & (c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta}) e^{i\alpha} & s_{23} c_{13} e^{i(\beta+\delta)} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -(c_{12} s_{23} + s_{12} c_{23} s_{13} e^{i\delta}) e^{i\alpha} & c_{23} c_{13} e^{i(\beta+\delta)} \end{pmatrix}$$



Insert (known) Neutrino Data

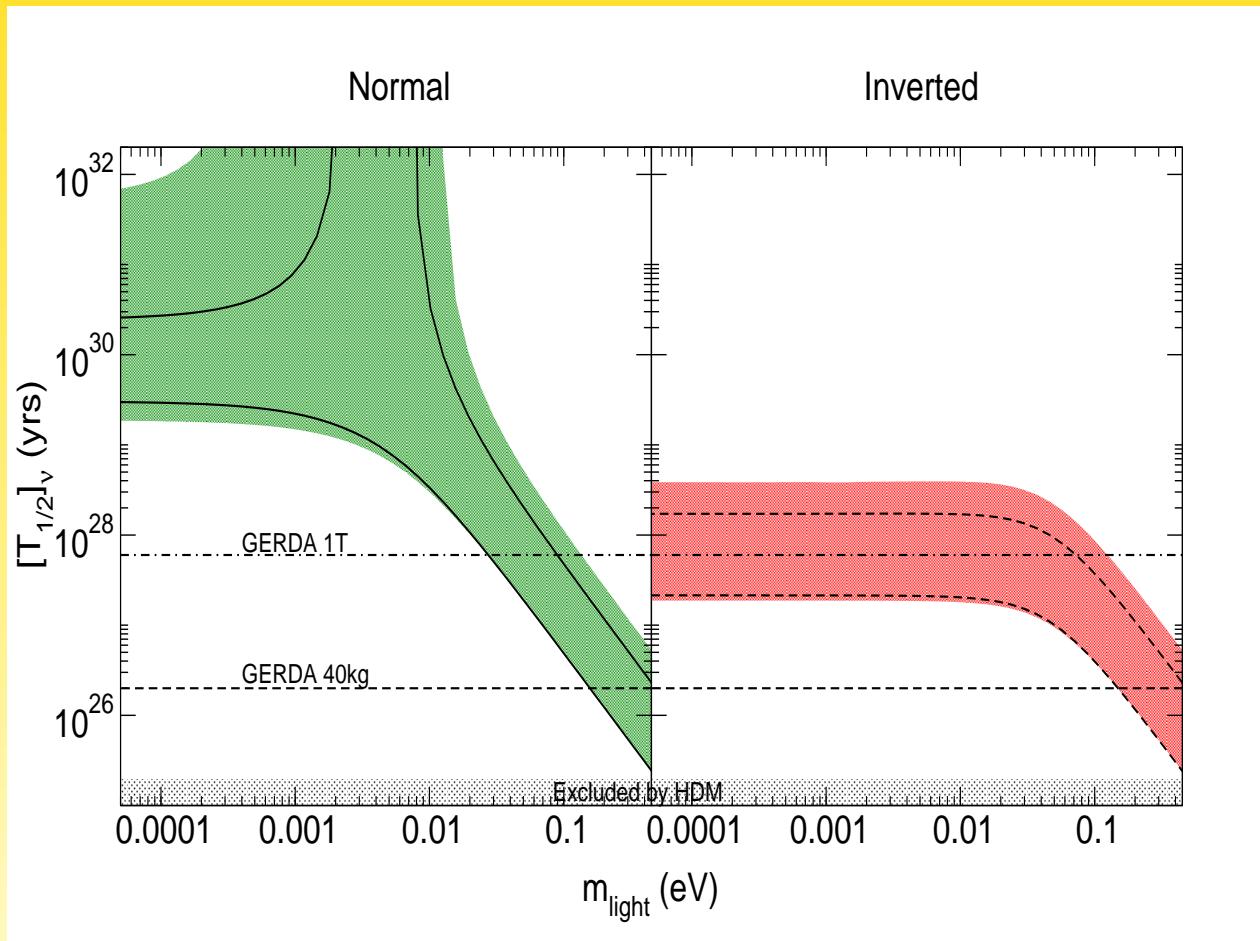


The usual plot

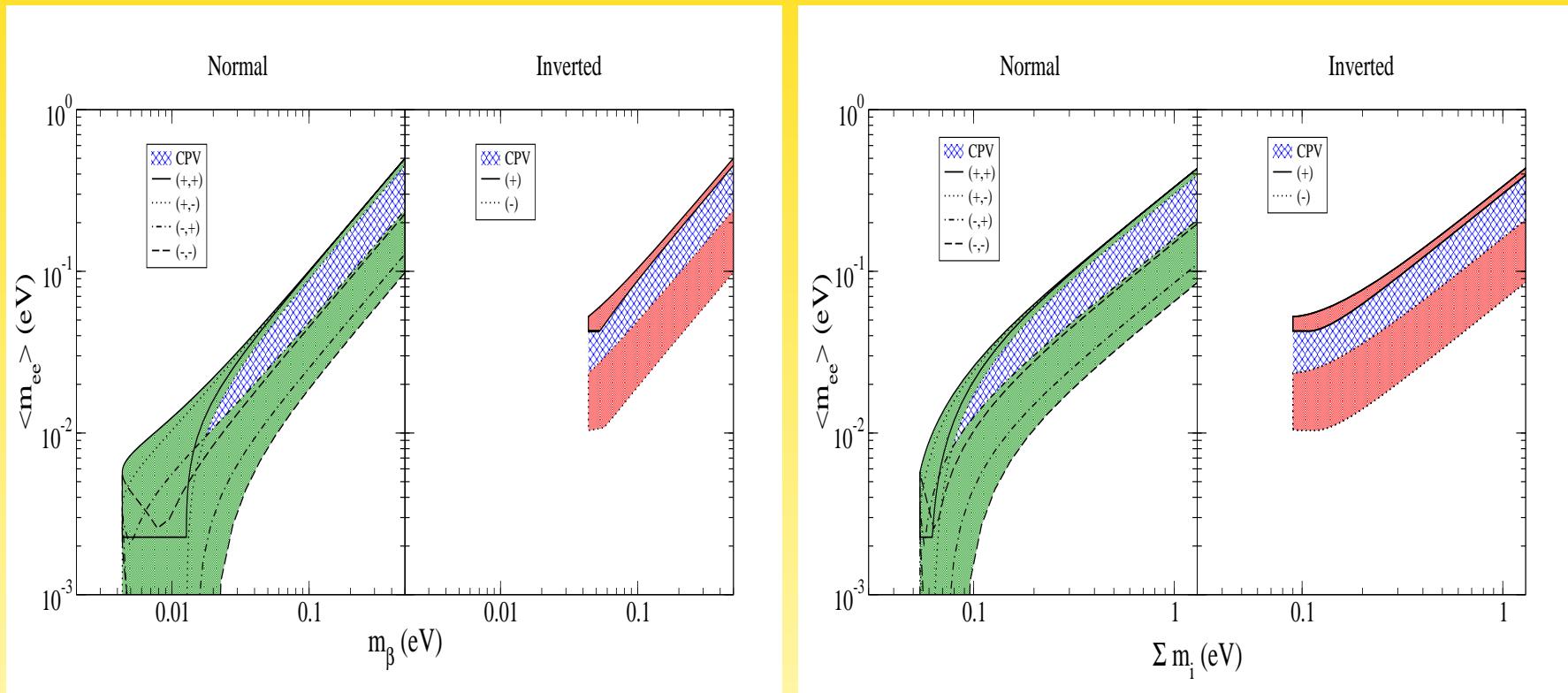


The usual plot

(life-time instead of $|m_{ee}|$)



Plot against other observables



Complementarity of $|m_{ee}| = U_{ei}^2 m_i$, $m_\beta = \sqrt{|U_{ei}|^2 m_i^2}$ and $\Sigma = \sum m_i$

Neutrino Mass

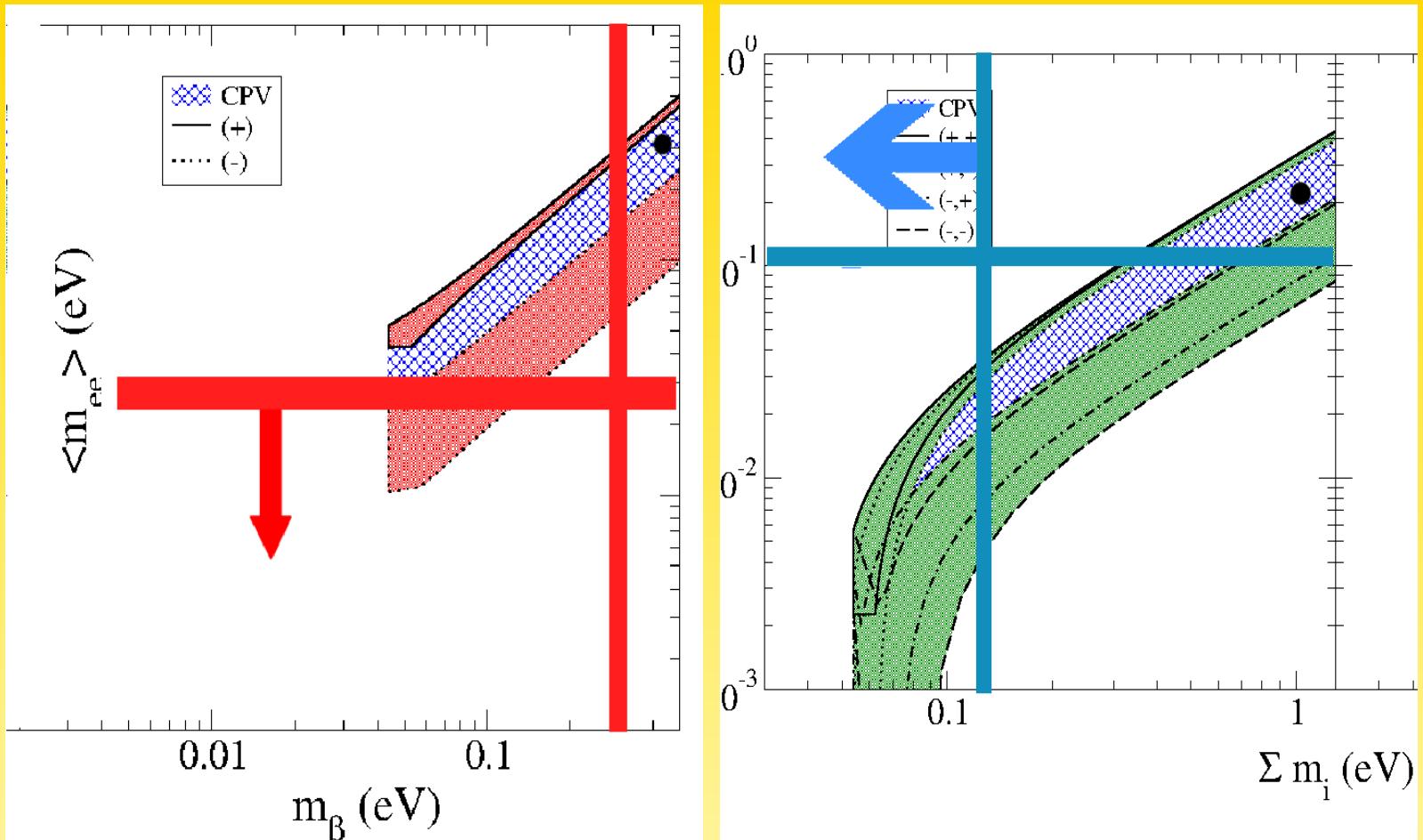
$$m(\text{heaviest}) \gtrsim \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV}$$

3 complementary methods to measure neutrino mass:

Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum U_{ei} ^2 m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	0.7	0.3	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$ \sum U_{ei}^2 m_i $	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

Neutrino Mass Complementarity

- have entered the era of complementarity:
 - cosmology limits rule out that light neutrinos satisfy current $0\nu\beta\beta$ -limits
 - $0\nu\beta\beta$ -limits rule out that neutrinos saturate Mainz/Troitsk limit
- interesting possibilities (if inconsistencies arise)...



CP violation!

Dirac neutrinos!

Something else does $0\nu\beta\beta$!

Neutrino Mass Matrix

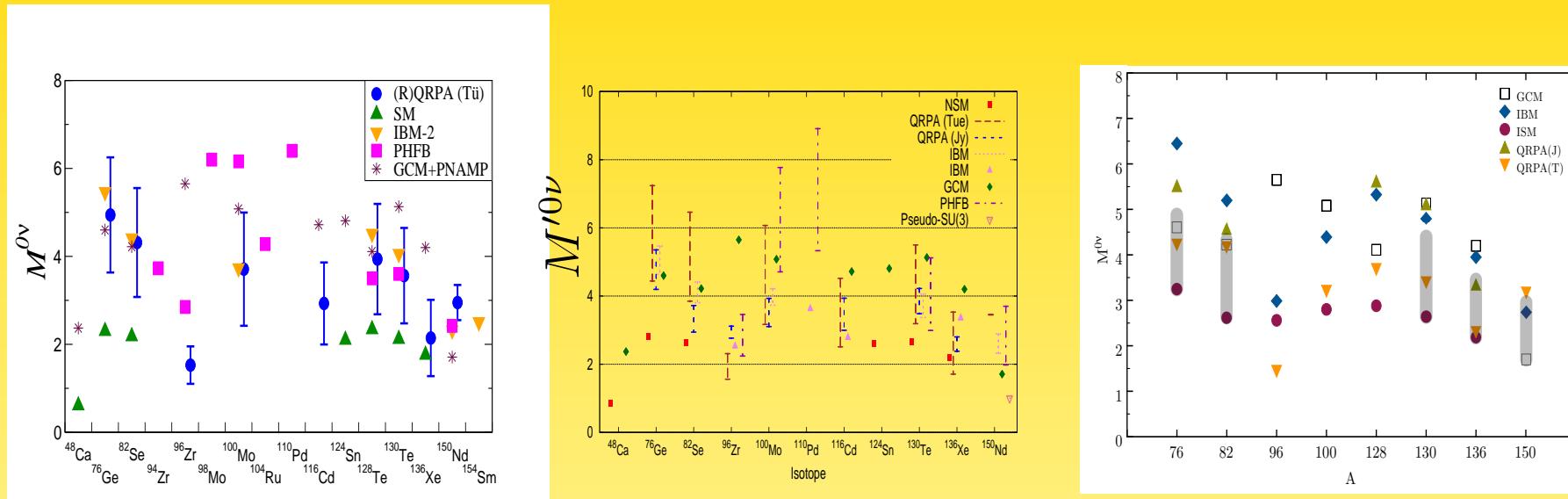
KATRIN			$0\nu\beta\beta$		cosmology		
	yes	no	yes	no	yes	no	
KATRIN	yes	-	-	QD + Majorana	QD + Dirac	QD	N-SC
	no	-	-	N-SI	low IH or NH or Dirac	$m_\nu \lesssim 0.1 \text{ eV}$ or N-SC	NH
$0\nu\beta\beta$	yes	+	+	-	-	(IH or QD) + Majorana	N-SC or N-SI
	no	+	+	-	-	low IH or (QD + Dirac)	NH
cosmology	yes	+	+	+	+	-	-
	no	+	+	+	+	-	-

From life-time to particle physics: Nuclear Matrix Elements



Dark Lord Of The Sith by G. Røn, 1999. Star Wars: Ord Mantell. www.starwars.priv.pl

From life-time to particle physics: Nuclear Matrix Elements



current status, details, ranges, uncertainties:

Fedor Simkovic, Thursday

Xe vs. Ge

Xe-limit is stronger than Ge-limit when:

$$T_{\text{Xe}} > T_{\text{Ge}} \frac{G_{\text{Ge}}}{G_{\text{Xe}}} \left| \frac{\mathcal{M}_{\text{Ge}}}{\mathcal{M}_{\text{Xe}}} \right|^2 \text{ yrs}$$

Method	NME	
	$\mathcal{M}_{0\nu}({}^{76}\text{Ge})$	$\mathcal{M}_{0\nu}({}^{136}\text{Xe})$
EDF(U)	4.60	4.20
ISM(U)	2.81	2.19
IBM-2	5.42	3.33
pnQRPA(U)	5.18	3.16
SRQRPA-B	5.82	3.36
SRQRPA-A	4.75	2.29
QRPA-B	5.57	2.46
QRPA-A	5.16	2.18
<i>SkM-HFB-QRPA</i>	5.09	1.89

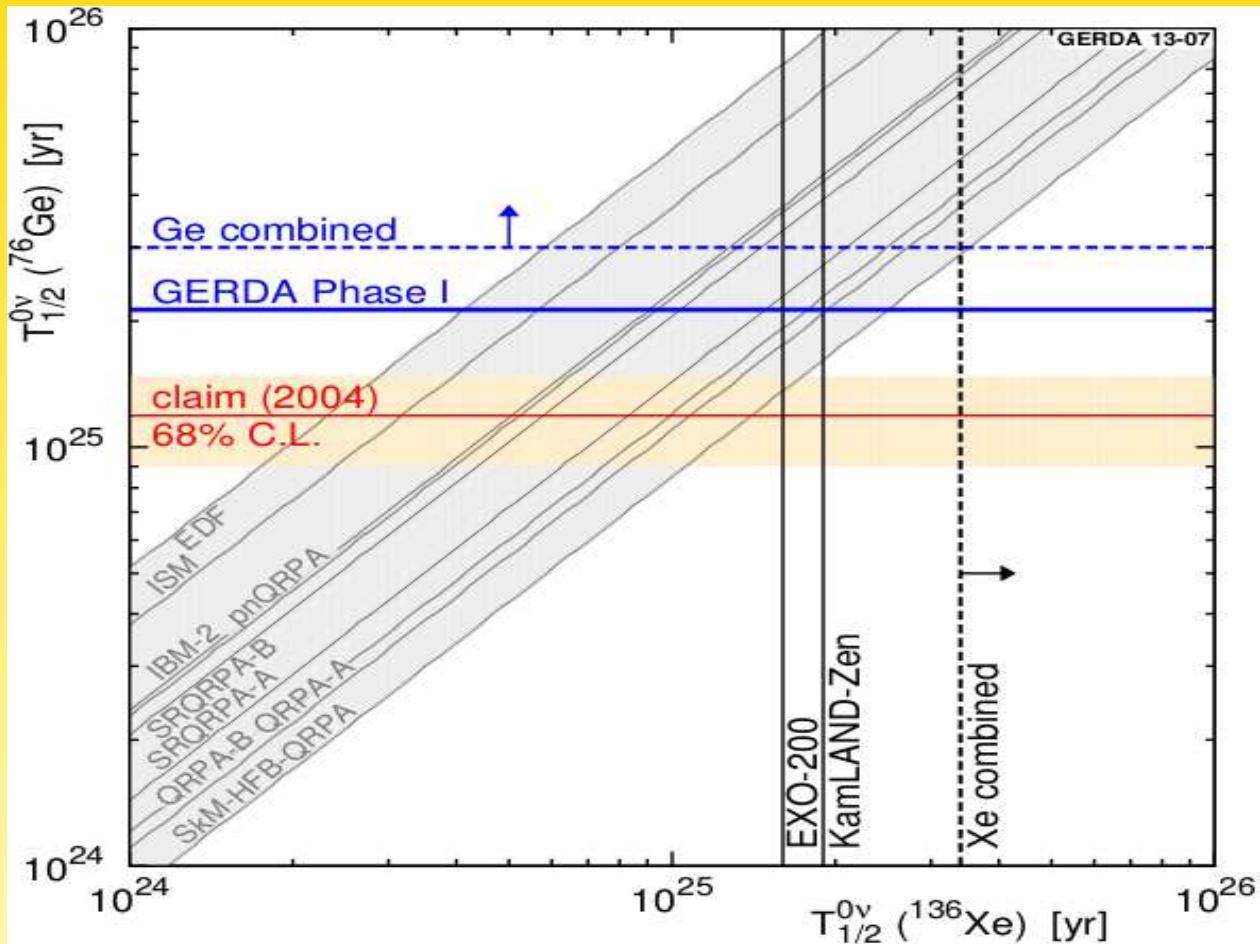
small QRPA-NME for Xe! ([Mustonen, Engel, 1301.6997](#))

↔ small overlap in initial and final mean fields

NME	Limit on $ m_{ee} $ (eV)			
	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	0.32	0.27	0.15	0.11
ISM(U)	0.52	0.44	0.28	0.21
IBM-2	0.27	0.23	0.19	0.14
pnQRPA(U)	0.28	0.24	0.20	0.15
SRQRPA-B	0.25	0.21	0.18	0.14
SRQRPA-A	0.31	0.26	0.27	0.20
QRPA-A	0.28	0.24	0.29	0.21
<i>SkM-HFB-QRPA</i>	<i>0.29</i>	<i>0.24</i>	<i>0.33</i>	<i>0.25</i>

Bhupal Dev, Goswami, Mitra, W.R., 1305.0056

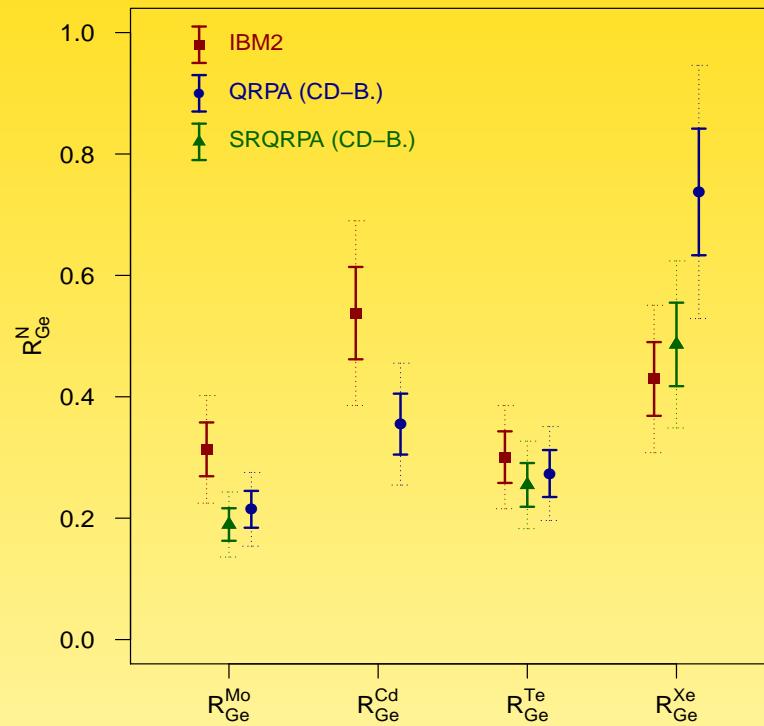
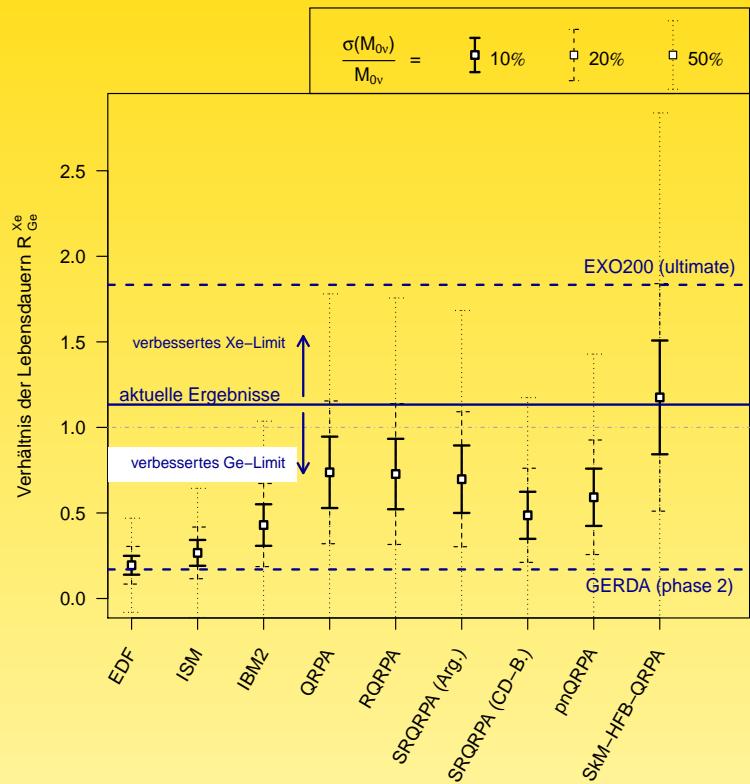
Xe vs. Ge



GERDA, 1307.4720

(Ge vs. Klapdor: see next talk by Bernhard Schwingenheuer)

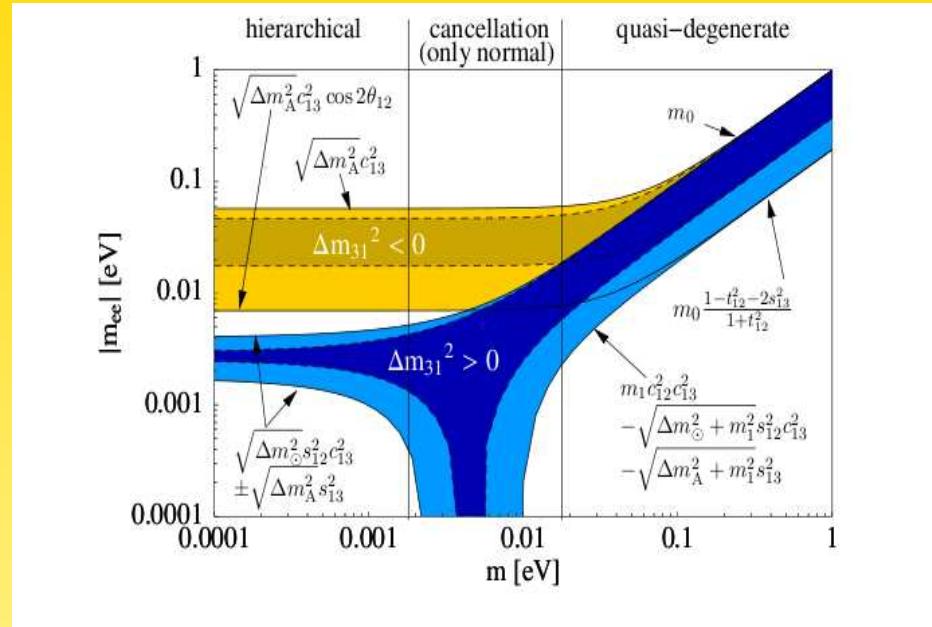
Testing NME calculations with multi-isotope determination?



Lifetime ratios with respect to Ge

Bleher, W.R., in preparation

Inverted Ordering



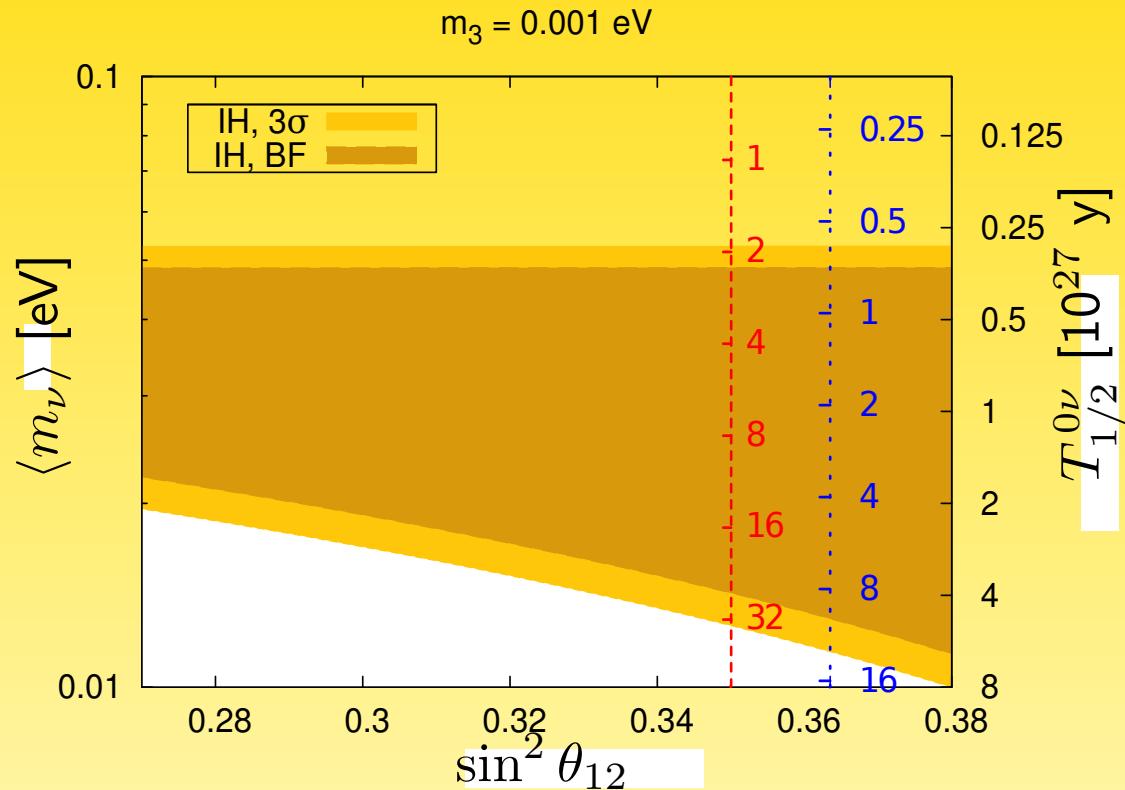
Nature provides 2 scales:

$$|m_{ee}|_{\max}^{\text{IH}} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \quad \text{and} \quad |m_{ee}|_{\min}^{\text{IH}} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \cos 2\theta_{12}$$

requires $\mathcal{O}(10^{26} \dots 10^{27})$ yrs

is the lower limit $|m_{ee}|_{\min}^{\text{IH}}$ fixed?

Inverted Hierarchy



Dueck, W.R., Zuber, PRD **83**

Ruling out Inverted Hierarchy

$$|m_{ee}|_{\min}^{\text{IH}} = (1 - |U_{e3}|^2) \sqrt{|\Delta m_A^2|} (1 - 2 \sin^2 \theta_{12})$$
$$= \begin{cases} (0.012 \dots 0.023) \text{ eV} & (\text{Valle et al.}) \\ (0.013 \dots 0.024) \text{ eV} & (\text{Schwetz et al.}) \\ (0.013 \dots 0.024) \text{ eV} & (\text{Fogli+Lisi et al.}) \end{cases}$$

(want small $|U_{e3}|$, large $|\Delta m_A^2|$, small $\sin^2 \theta_{12}$)

Current 3σ range of $\sin^2 \theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|_{\min}^{\text{IH}}$

\Rightarrow combined factor of ~ 16 in $M \times t \times B \times \Delta E$

\Rightarrow need precision determination of θ_{12} !

Dueck, W.R., Zuber, PRD 83

Ruling out Inverted Hierarchy

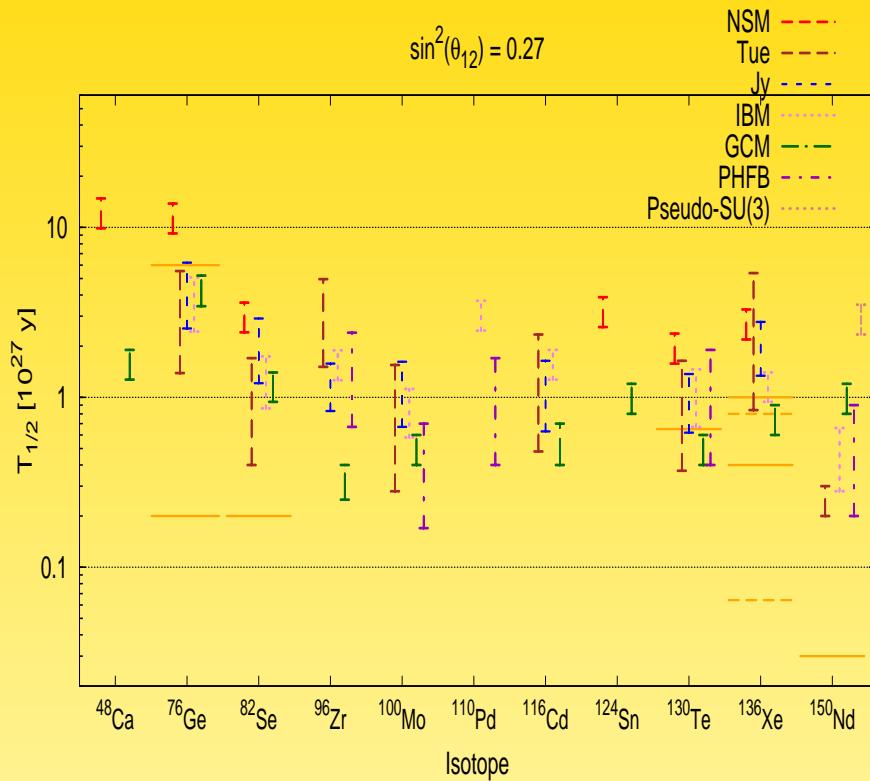
$$|m_{ee}|_{\min}^{\text{IH}} = (1 - |U_{e3}|^2) \sqrt{|\Delta m_A^2|} (1 - 2 \sin^2 \theta_{12})$$
$$= \begin{cases} (0.012 \dots 0.023) \text{ eV} & \Rightarrow \text{factor 15} \quad (\text{Valle et al.}) \\ (0.013 \dots 0.024) \text{ eV} & \Rightarrow \text{factor 9} \quad (\text{Schwetz et al.}) \\ (0.013 \dots 0.024) \text{ eV} & \Rightarrow \text{factor 13} \quad (\text{Fogli+Lisi et al.}) \end{cases}$$

(want small $|U_{e3}|$, large $|\Delta m_A^2|$, small $\sin^2 \theta_{12}$)

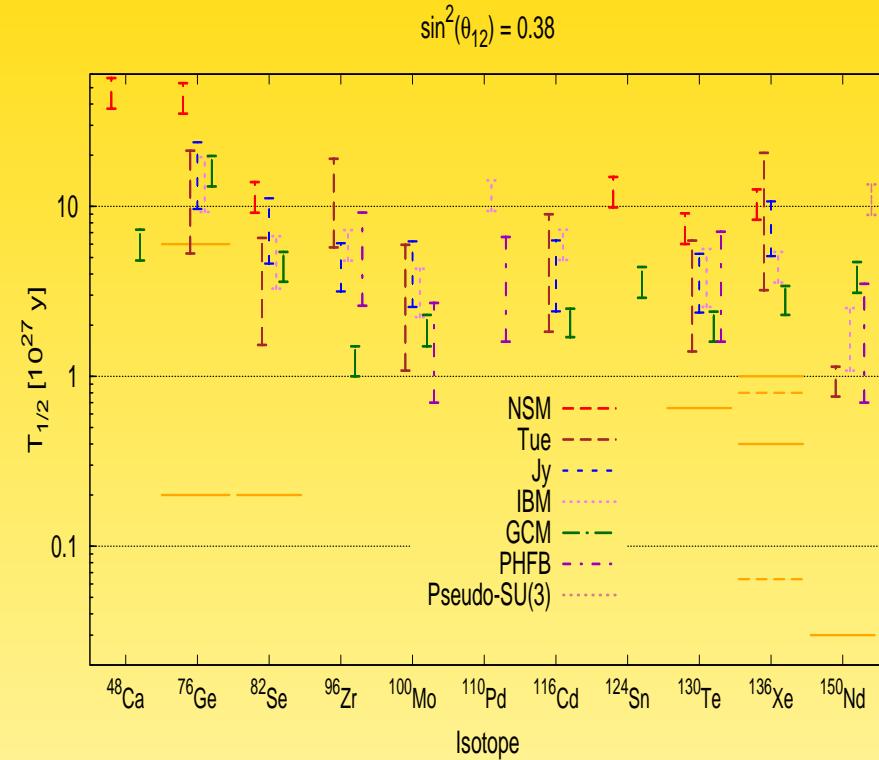
Current 3σ range of $\sin^2 \theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|_{\min}^{\text{IH}}$
 \Rightarrow combined factor of ~ 16 in $M \times t \times B \times \Delta E$
 \Rightarrow need precision determination of $\theta_{12}!$

Dueck, W.R., Zuber, PRD 83

Ruling out Inverted Hierarchy



$$\sin^2 \theta_{12} = 0.27$$



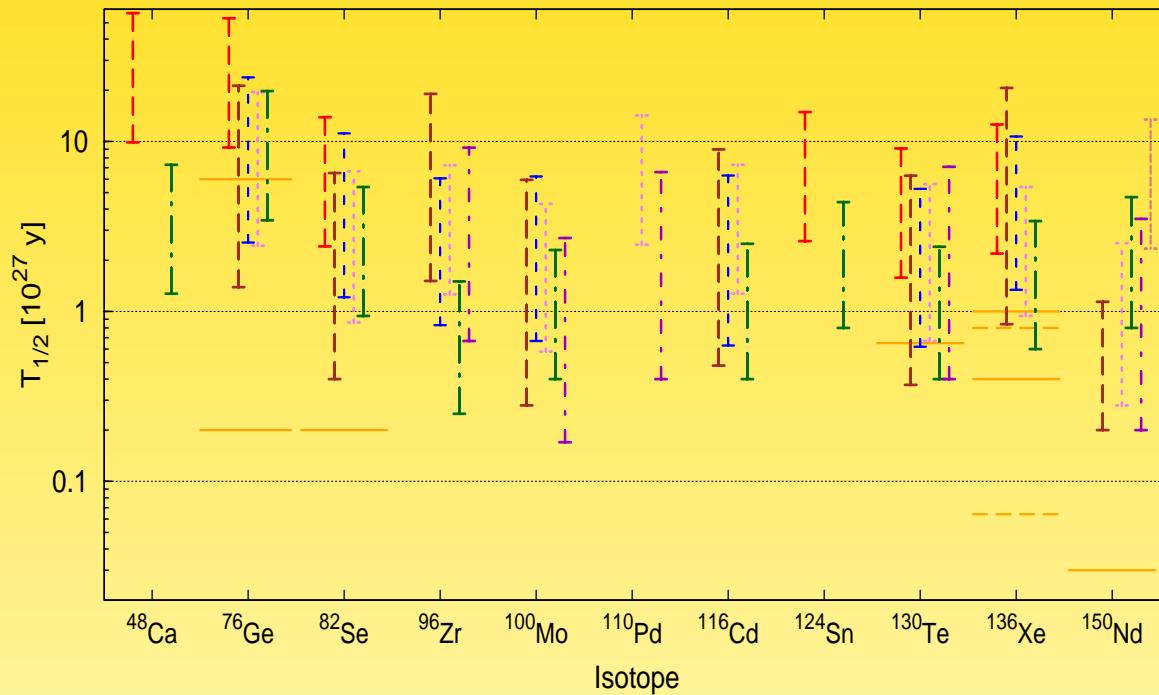
$$\sin^2 \theta_{12} = 0.38$$

spread due to NMEs **and due to θ_{12} !!**

same order as NMEs!

Ruling out Inverted Hierarchy

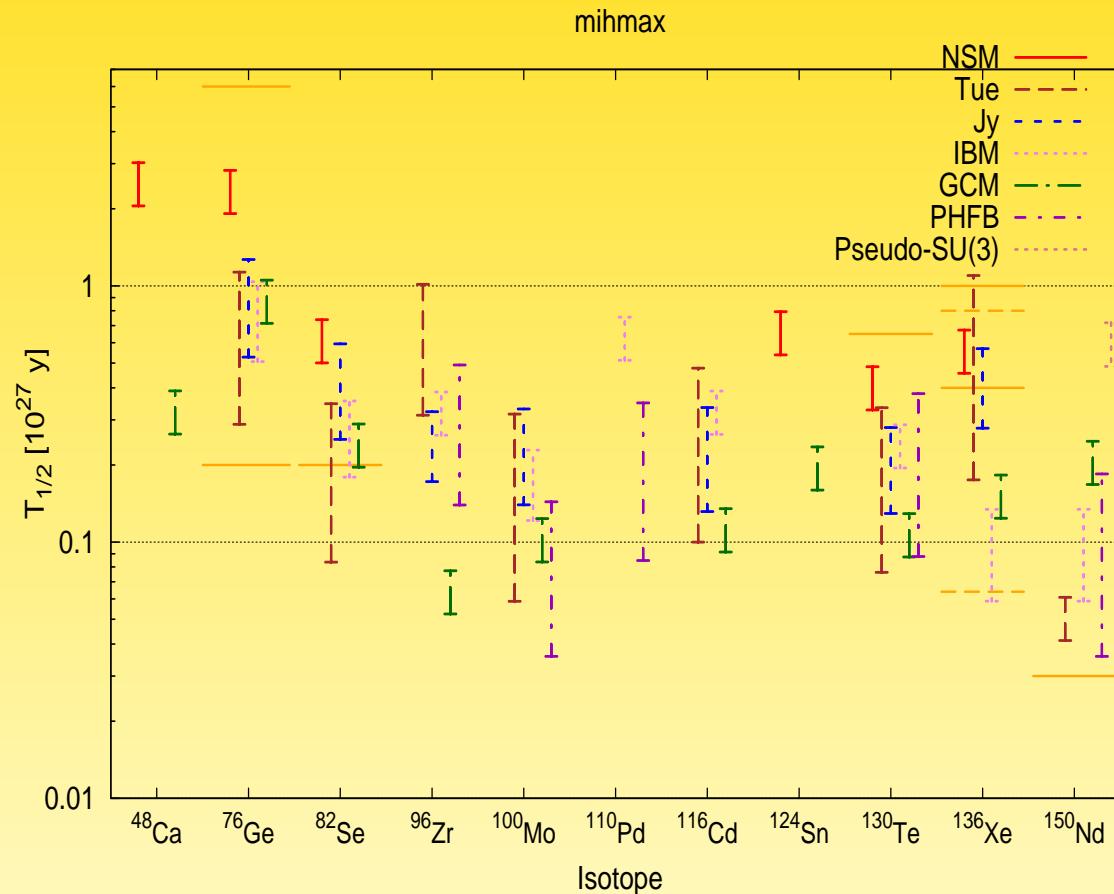
$$0.27 < \sin^2(\theta_{12}) < 0.38$$



spread due to NMEs **and due to $\theta_{12}!!$**
same order as NMEs!

Testing Inverted Hierarchy

lifetime to enter the IH regime



With $0\nu\beta\beta$ one can

- test lepton number violation
- test Majorana nature of neutrinos
- probe neutrino mass scale
- extract Majorana phase
- test flavor symmetry models
- constrain inverted ordering

conceptually, it would increase our belief in

- seesaw mechanism
- leptogenesis
- GUTs

Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

$$10_H \ (\leftrightarrow H), \ \overline{126}_H \ (\leftrightarrow F), \ 120_H \ (\leftrightarrow G)$$

Gives relation for mass matrices:

$$m_{\text{up}} \propto r(H + sF + it_u G)$$

$$m_{\text{down}} \propto H + F + iG$$

$$m_D \propto r(H - 3sF + it_D G)$$

$$m_\ell \propto H - 3F + it_l G$$

$$M_R \propto r_R^{-1} F$$

Numerical fit including RG, Higgs, θ_{13}

Dueck, W.R., 1306.4468

Predictions of $SO(10)$ theories

Model	Fit	$ m_{ee} $	m_0	M_3	χ^2
		[meV]	[meV]	[GeV]	
$10_H + \overline{126}_H$	NH	0.49	2.40	3.6×10^{12}	23.0
$10_H + \overline{126}_H + SS$	NH	0.44	6.83	1.1×10^{12}	3.29
<hr/>					
$10_H + \overline{126}_H + 120_H$	NH	2.87	1.54	9.9×10^{14}	11.2
$10_H + \overline{126}_H + 120_H + SS$	NH	0.78	3.17	4.2×10^{13}	6.9×10^{-6}
<hr/>					
$10_H + \overline{126}_H + 120_H$	IH	35.52	30.2	1.1×10^{13}	13.3
$10_H + \overline{126}_H + 120_H + SS$	IH	24.22	12.0	1.2×10^{13}	0.6
<hr/>					

$10_H + \overline{126}_H$: 19 free parameters

$10_H + \overline{126}_H + 120_H$: 18 free parameters

20 (19) observables to be fitted

Light Sterile Neutrinos??

- reactor anomaly
- Gallium anomaly
- LSND/MiniBooNE
- cosmology
- BBN
- r -process nucleosynthesis in Supernovae

New neutrino state with $\Delta m^2 \sim 1 \text{ eV}^2$ and $|U_{e4}| \sim 0.1$?

Sterile Neutrinos and $0\nu\beta\beta$

- recall: $|m_{ee}|_{\text{NH}}^{\text{act}}$ can vanish and $|m_{ee}|_{\text{IH}}^{\text{act}} \sim 0.03$ eV cannot vanish
- $|m_{ee}| = \underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta}}_{m_{ee}^{\text{act}}} + \underbrace{|U_{e4}|^2 m_4 e^{2i\Phi_1}}_{m_{ee}^{\text{st}}}$
- sterile contribution to $0\nu\beta\beta$ (assuming 1+3):

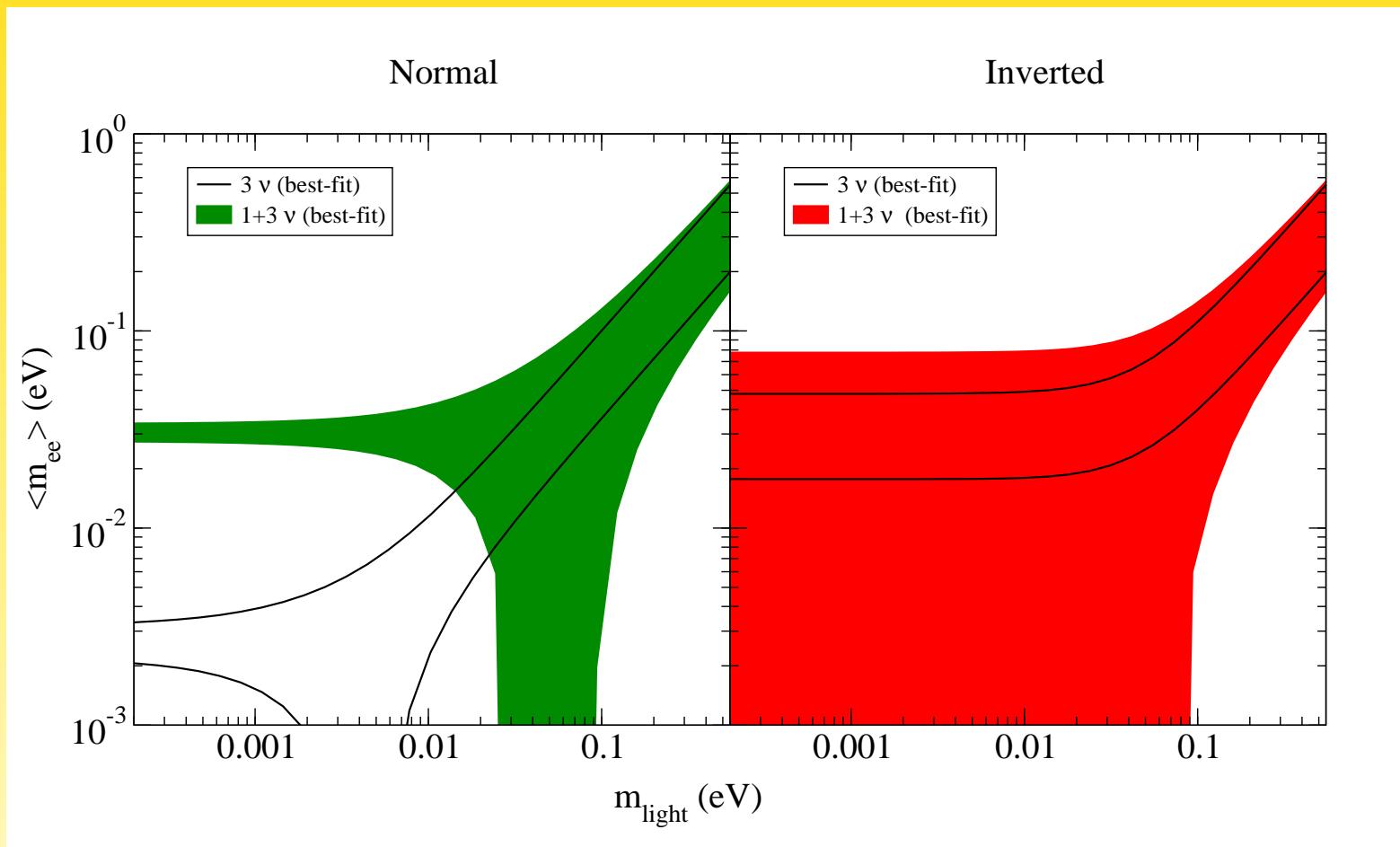
$$|m_{ee}|^{\text{st}} \simeq \sqrt{\Delta m_{\text{st}}^2} |U_{e4}|^2 \left\{ \begin{array}{l} \gg |m_{ee}|_{\text{NH}}^{\text{act}} \\ \simeq |m_{ee}|_{\text{IH}}^{\text{act}} \end{array} \right.$$

$\Rightarrow |m_{ee}|_{\text{NH}}$ cannot vanish and $|m_{ee}|_{\text{IH}}$ can vanish!

\Rightarrow usual phenomenology gets completely turned around!

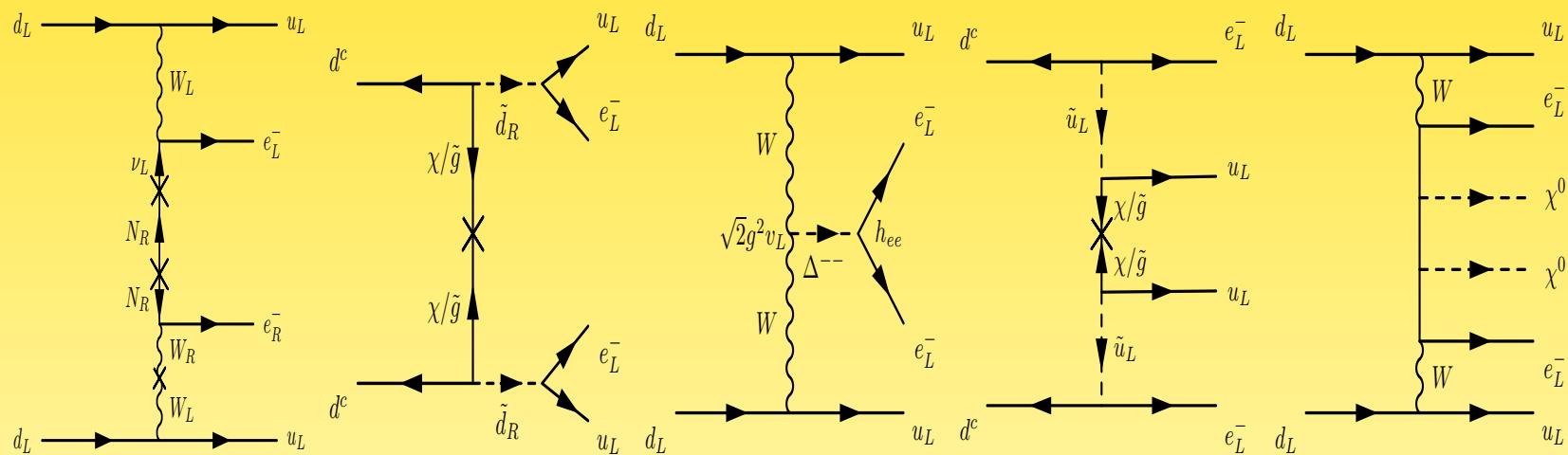
Barry, W.R., Zhang, JHEP 1107; Giunti *et al.*, PRD 87; Girardi, Meroni, Petcov, 1308.5802

Usual plot gets completely turned around!



Non-Standard Interpretations:

There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism

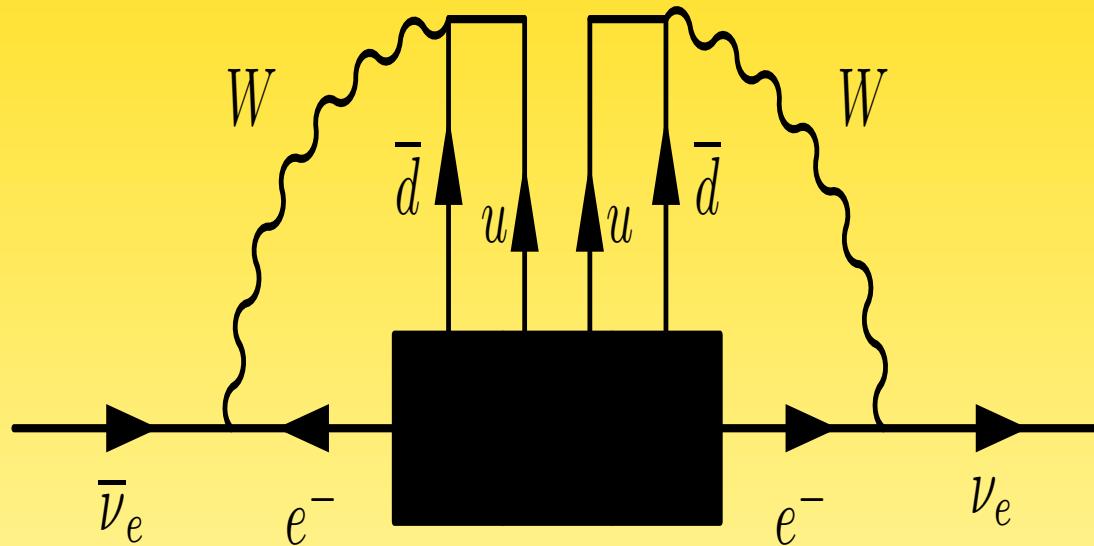


Clear experimental signature:

KATRIN and/or cosmology see nothing but $0\nu\beta\beta$ does

Schechter-Valle theorem:

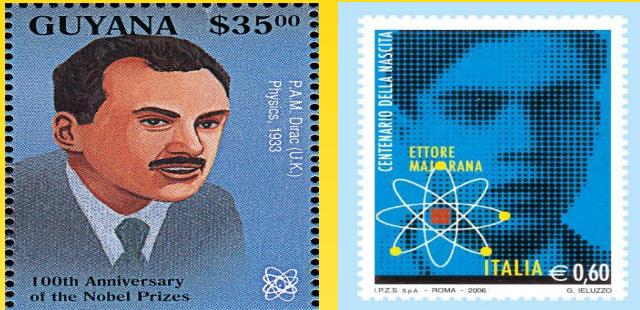
no matter what process, neutrinos are Majorana:



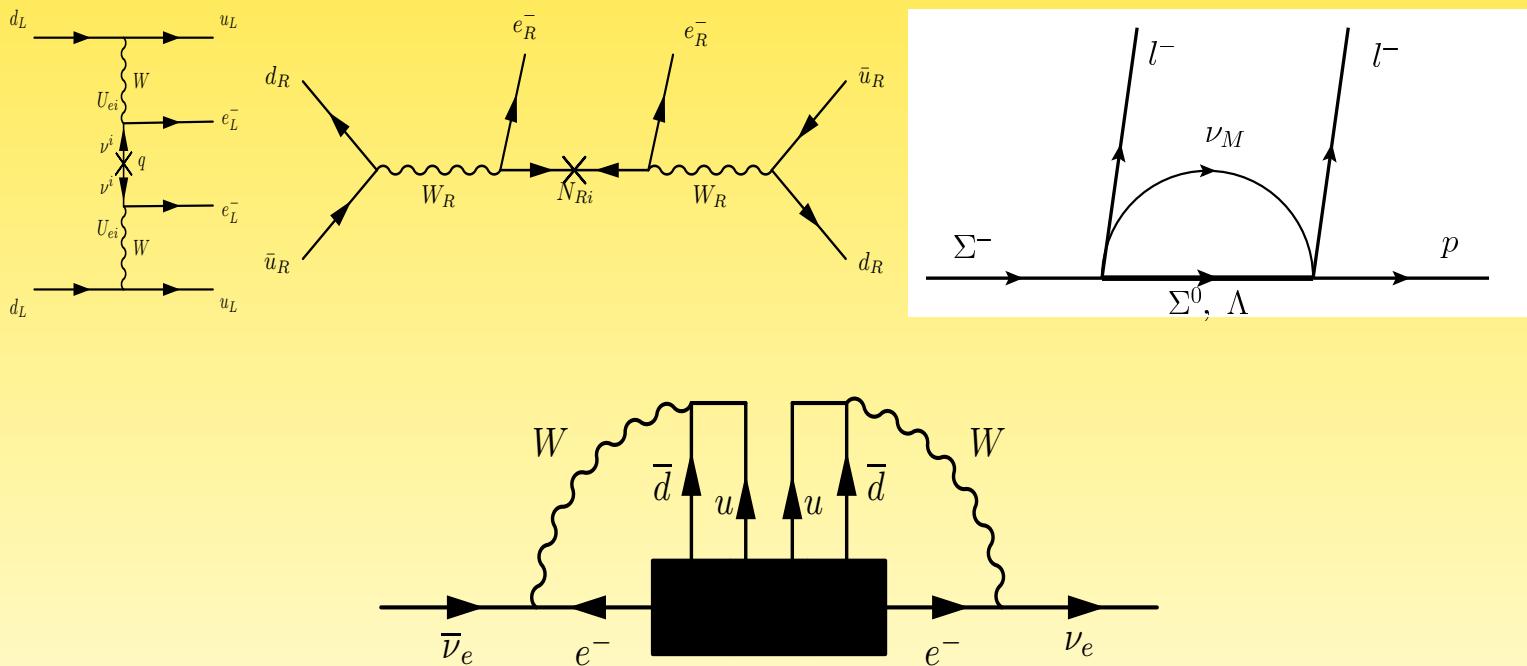
is 4 loop diagram: $m_\nu^{\text{BB}} \sim \frac{G_F^2}{(16\pi^2)^4} \text{MeV}^5 \sim 10^{-25} \text{ eV}$

explicit calculation: Duerr, Lindner, Merle, 1105.0901

Dirac or Majorana neutrinos?

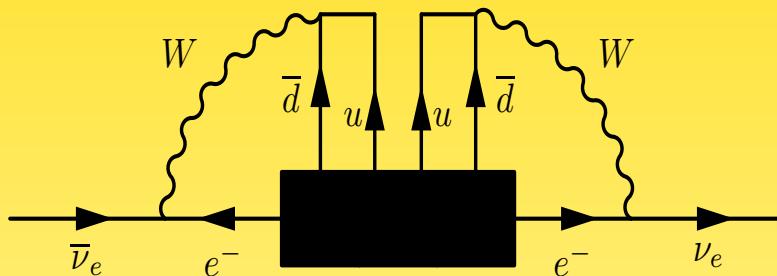


proof neutrinos are Majorana: observe (e.g.) neutrinoless double beta decay



Dirac or Majorana neutrinos?

Actually not that straightforward:



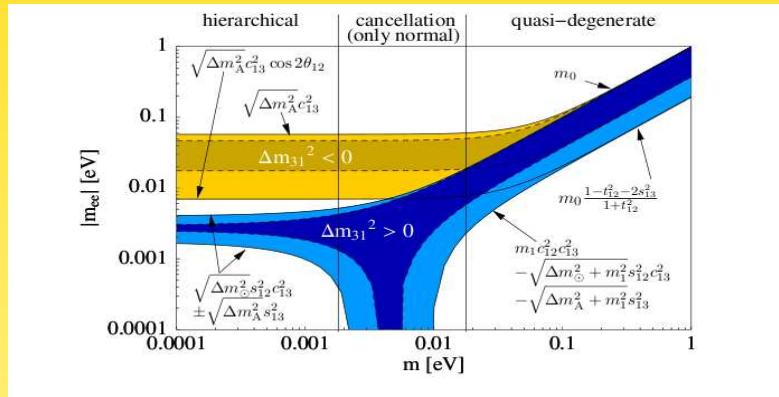
is 4 loop diagram

- neutrinos could be mainly Dirac
- some other process does $0\nu\beta\beta$
- m_ν^{BB} makes them Pseudo-Dirac

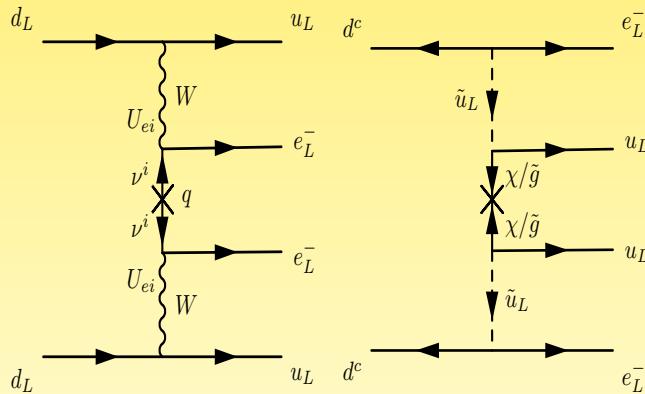
Dirac or Majorana neutrinos?

proof neutrinos are Dirac: not so easy...

$|m_{ee}|$ could be zero...



or cancelled by other contribution...



Do Dirac neutrinos imply that there is no Lepton Number Violation?

possible to construct $U(1)_{B-L}$ model with $\chi \sim -2$ and $\phi \sim 4$

$$\begin{aligned}\mathcal{L} = & \left(y_{\alpha\beta} \bar{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta} \chi \bar{\nu}_{R,\alpha} \nu_{R,\beta}^c + h.c. \right) + \sum_{X=H,\phi,\chi} (\mu_X^2 |X|^2 + \lambda_X |X|^4) \\ & + \lambda_{H\phi} |H|^2 |\phi|^2 + \lambda_{H\chi} |H|^2 |\chi|^2 + \lambda_{\chi\phi} |\chi|^2 |\phi|^2 - (\mu \phi \chi^2 + h.c.)\end{aligned}$$

break it by allowing only scalar ϕ to obtain VEV:

\Rightarrow neutrinos are Dirac particles, and Lepton Number violated by 4 units!

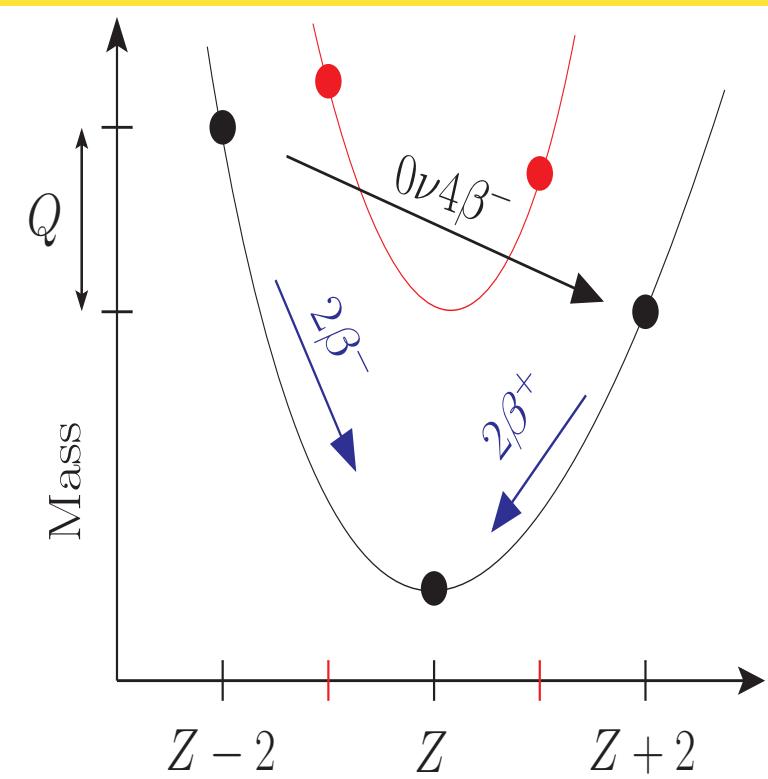
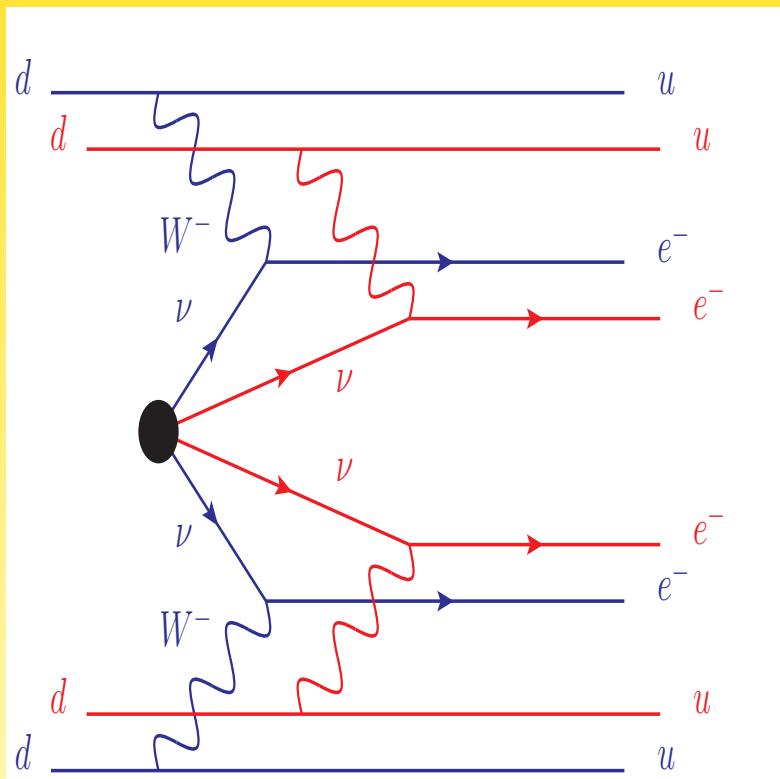
\Rightarrow neutrinoless double beta decay forbidden...how to test?

Heeck, W.R., EPL 103

Does Dirac neutrinos mean there is no Lepton Number Violation?

neutrinos are Dirac particles, and Lepton Number violated by 4 units!

⇒ observable: neutrinoless quadruple beta decay $(A, Z) \rightarrow (A, Z + 4) + 4 e^-$



Heeck, W.R., EPL 103

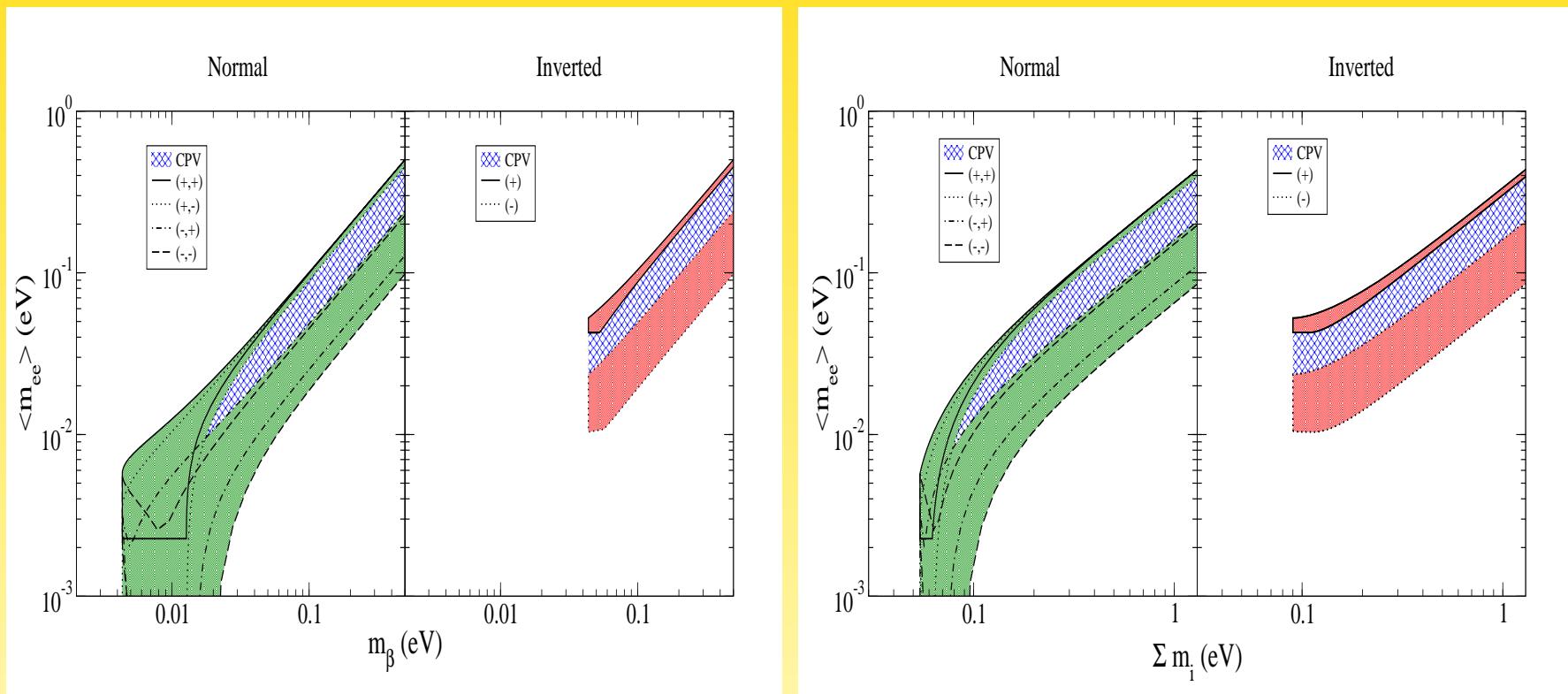
mechanism	physics parameter	current limit	test
light neutrino exchange	$ U_{ei}^2 m_i $	0.4 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left \frac{S_{ei}^2}{M_i} \right $	$2 \times 10^{-8} \text{ GeV}^{-1}$	LFV, collider
heavy neutrino and RHC	$\left \frac{V_{ei}^2}{M_i M_W^4} \right $	$4 \times 10^{-16} \text{ GeV}^{-5}$	flavor, collider
Higgs triplet and RHC	$\left \frac{(M_R)_{ee}}{m_{\Delta_R}^2 M_W^4} \right $	$10^{-15} \text{ GeV}^{-5}$	flavor, collider e^- distribution
λ-mechanism with RHC	$\left \frac{U_{ei} \tilde{S}_{ei}}{M_W^2} \right $	$1.4 \times 10^{-10} \text{ GeV}^{-2}$	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan \zeta \left U_{ei} \tilde{S}_{ei} \right $	6×10^{-9}	flavor, collider, e^- distribution
short-range \mathcal{R}	$\frac{\left \lambda'_{111} \right }{\Lambda_{\text{SUSY}}^5}$ $\Lambda_{\text{SUSY}} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	$7 \times 10^{-18} \text{ GeV}^{-5}$	collider, flavor
long-range \mathcal{R}	$\left \sin 2\theta^b \lambda'_{131} \lambda'_{113} \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2} \right) \right $ $\sim \frac{G_F}{q} m_b \frac{\left \lambda'_{131} \lambda'_{113} \right }{\Lambda_{\text{SUSY}}^3}$	$2 \times 10^{-13} \text{ GeV}^{-2}$ $1 \times 10^{-14} \text{ GeV}^{-3}$	flavor, collider
Majorons	$ \langle g_\chi \rangle \text{ or } \langle g_\chi \rangle ^2$	$10^{-4} \dots 1$	spectrum, cosmology

Distinguishing Mechanisms

The inverse problem of $0\nu\beta\beta$

- 1.) Other observables (LHC, LFV, KATRIN, cosmology,...)
- 2.) Decay products (individual e^- energies, angular correlations, spectrum,...)
- 3.) Nuclear physics (multi-isotope, $0\nu\text{ECEC}$, $0\nu\beta^+\beta^+$,...)

1.) Distinguishing via other Observables



standard mechanism: KATRIN, cosmology

Energy Scale:

Note: *standard amplitude* for light Majorana neutrino exchange:

$$\mathcal{A}_l \simeq G_F^2 \frac{|m_{ee}|}{q^2} \simeq 7 \times 10^{-18} \left(\frac{|m_{ee}|}{0.5 \text{ eV}} \right) \text{ GeV}^{-5} \simeq 2.7 \text{ TeV}^{-5}$$

if new heavy particles are exchanged:

$$\mathcal{A}_h \simeq \frac{c}{M^5}$$

\Rightarrow for $0\nu\beta\beta$ holds:

$$1 \text{ eV} = 1 \text{ TeV}$$

\Rightarrow Phenomenology in colliders, LFV

Examples

- R -parity violating supersymmetry ([Allanach](#), [Paes](#), [Kom](#))
- TeV seesaw neutrinos ([Ibarra](#), [Petcov et al.](#); [Mitra](#), [Senjanovic](#), [Vissani](#))
- Left-right symmetric theories ([Senjanovic et al.](#); [Goswami et al.](#); [Parida et al.](#); [Barry, W.R.](#); [Lee, Bhupal Dev](#), [Mohapatra](#))
- Higher dimensional operators ([Hirsch et al.](#))
- etc.

Seesaw Formalism

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

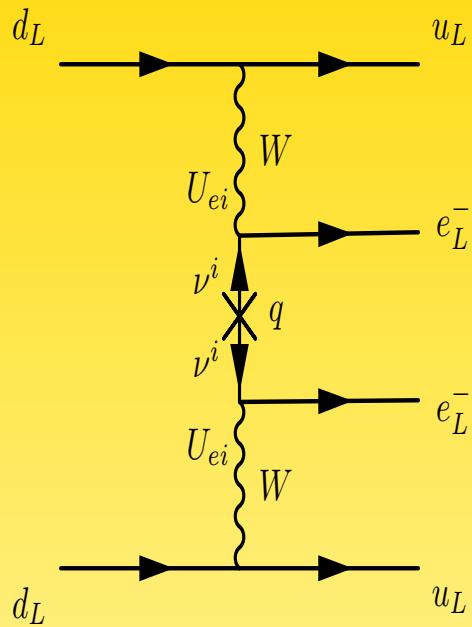
3 active neutrinos mix with sterile neutrinos via

$$\theta_{\alpha i} = (m_D M_R^{-1})_{\alpha i} = \frac{[m_D]_{\alpha i}}{M_i} = \mathcal{O}(\sqrt{m_\nu/M_R})$$

naively, N_R with TeV mass have mixing $\mathcal{O}(10^{-7})$

option: cancellations!

Light vs. heavy neutrinos



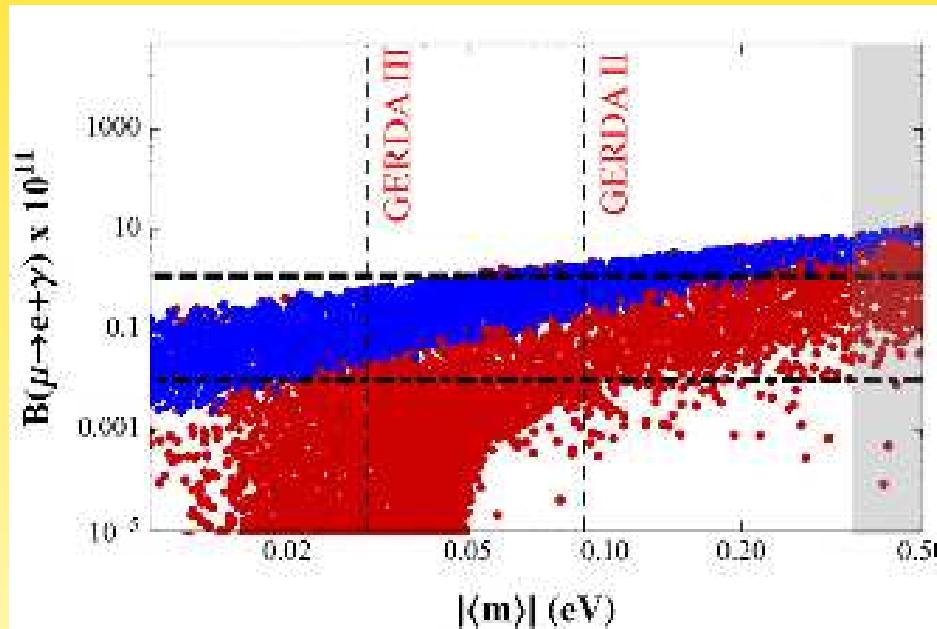
Amplitude proportional to

$$\frac{U_{ei}^2 m_i}{q^2 - m_i^2} \propto \begin{cases} U_{ei}^2 m_i & \text{for light neutrinos} \quad q^2 \gg m_i^2 \\ \frac{U_{ei}^2}{m_i} & \text{for heavy neutrinos} \quad q^2 \ll m_i^2 \end{cases}$$

TeV scale seesaw with sizable mixing

Casas-Ibarra Parametrization

$$m_D = iU \sqrt{m_\nu^{\text{diag}}} R \sqrt{M_R^{\text{diag}}} V_R^T$$



Ibarra, Molinaro, Petcov, PRD 84

Sterile Neutrinos, Seesaw and $0\nu\beta\beta$

- if the eV-steriles are from seesaw: individual cancellations in flavor symmetry models, e.g.:

$$U_{e2}^2 m_2 + U_{e4}^2 m_4 = 0$$

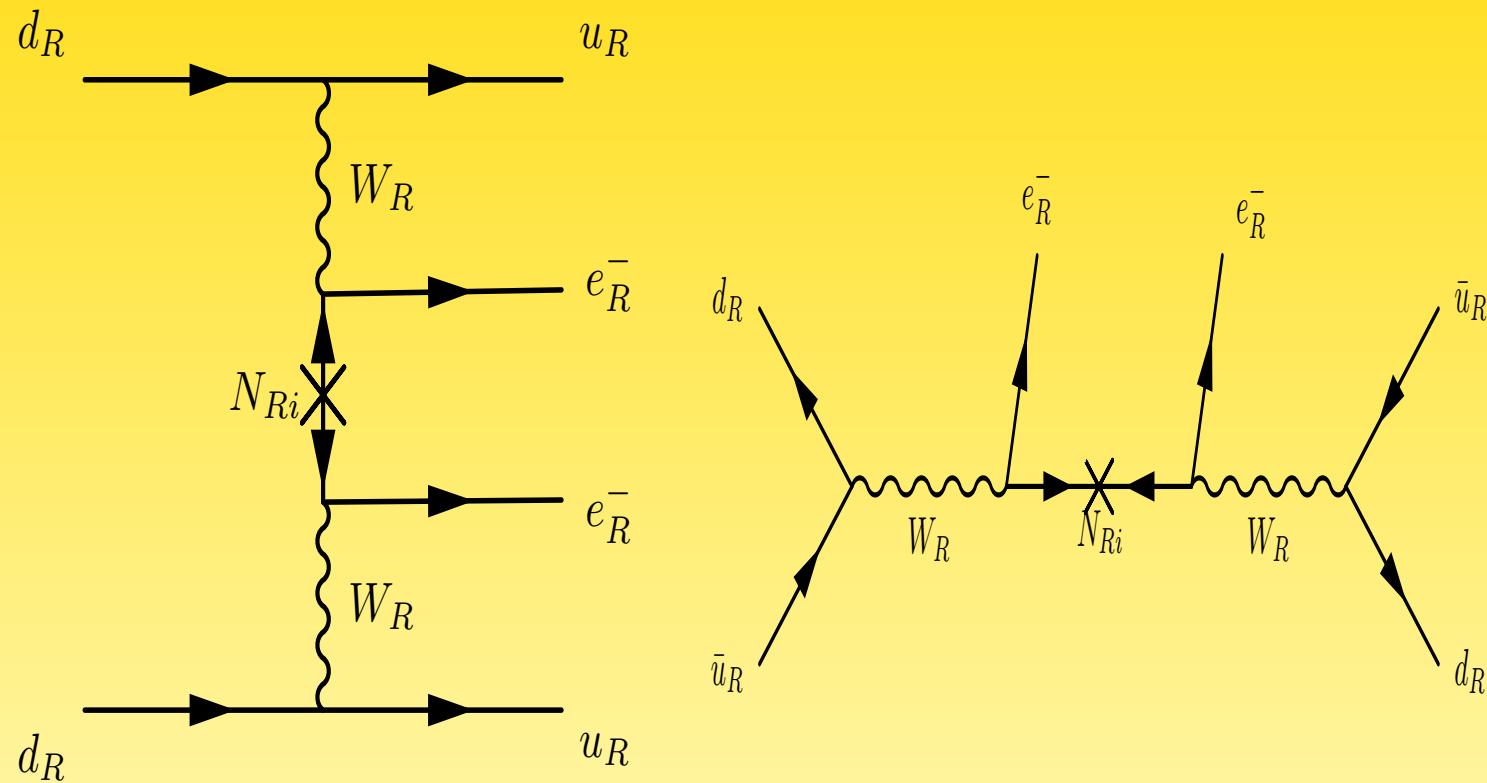
Barry, W.R., Zhang, JCAP 1201

- if seesaw scale is below 100 MeV: No double beta decay!

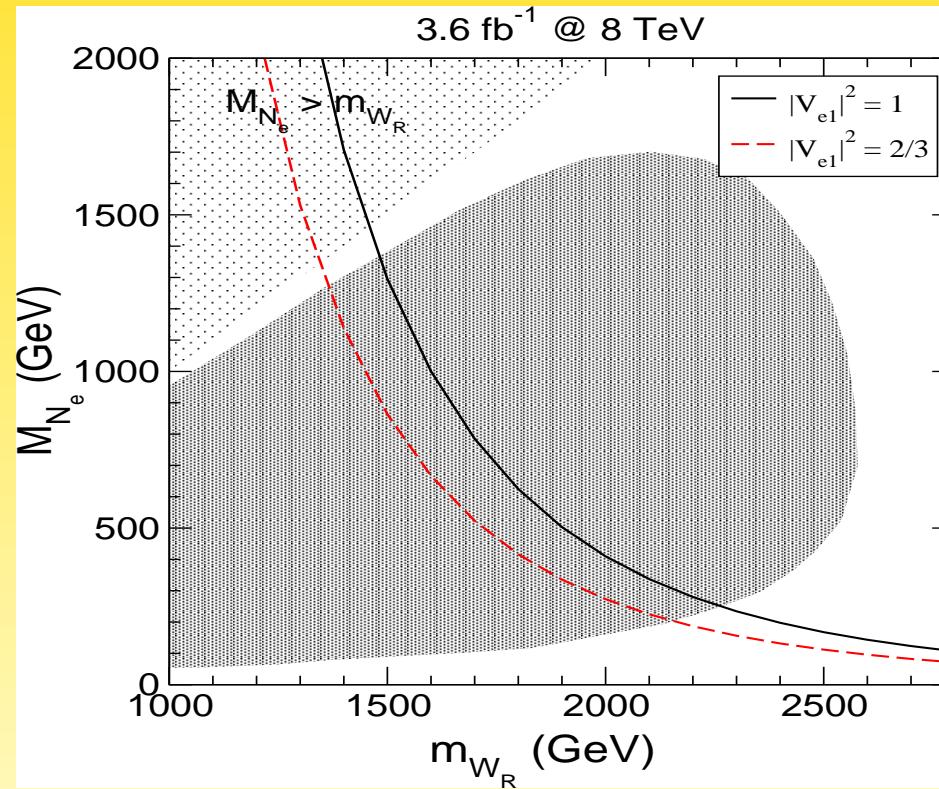
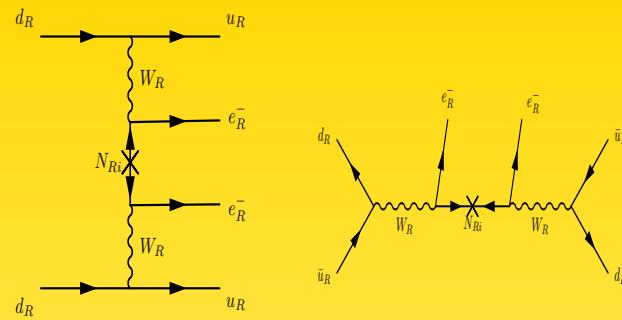
$$\sum_{i=1}^6 U_{ei}^2 m_i = 0 \text{ since } \mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = U \begin{pmatrix} m_\nu^{\text{diag}} & 0 \\ 0 & M_R^{\text{diag}} \end{pmatrix} U^T$$

de Gouvea, Jenkins, Vasudevan, PRD 75

Left-right symmetry

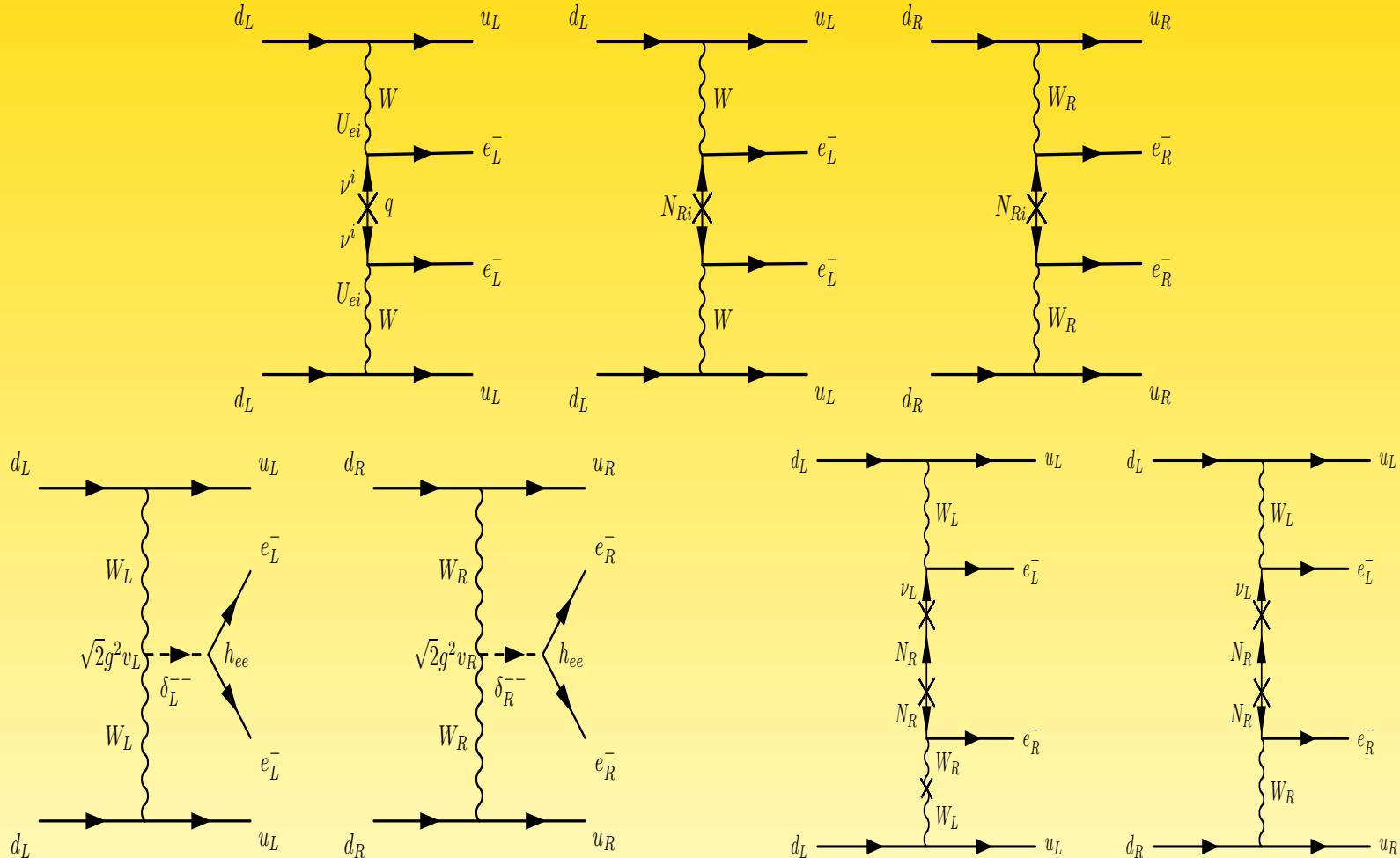


Senjanovic, Keung, 1983; Senjanovic *et al.*, 1011.3522; 1103.1627

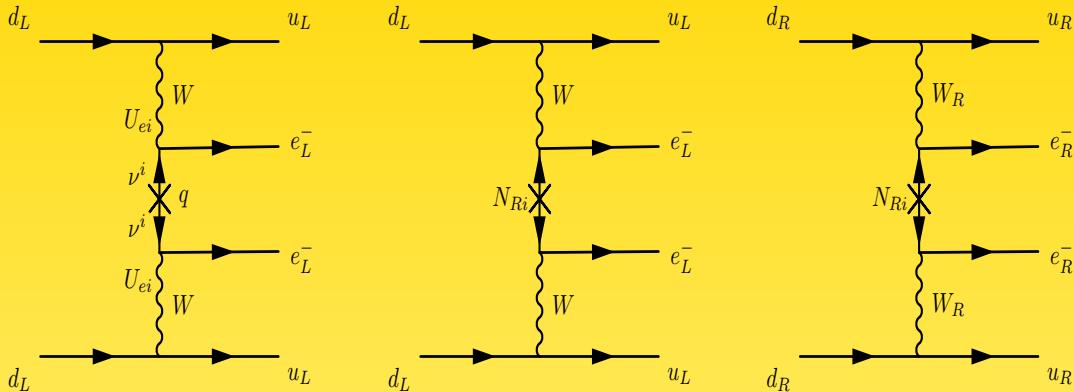


Barry, W.R., 1303.6324

Left-right symmetry



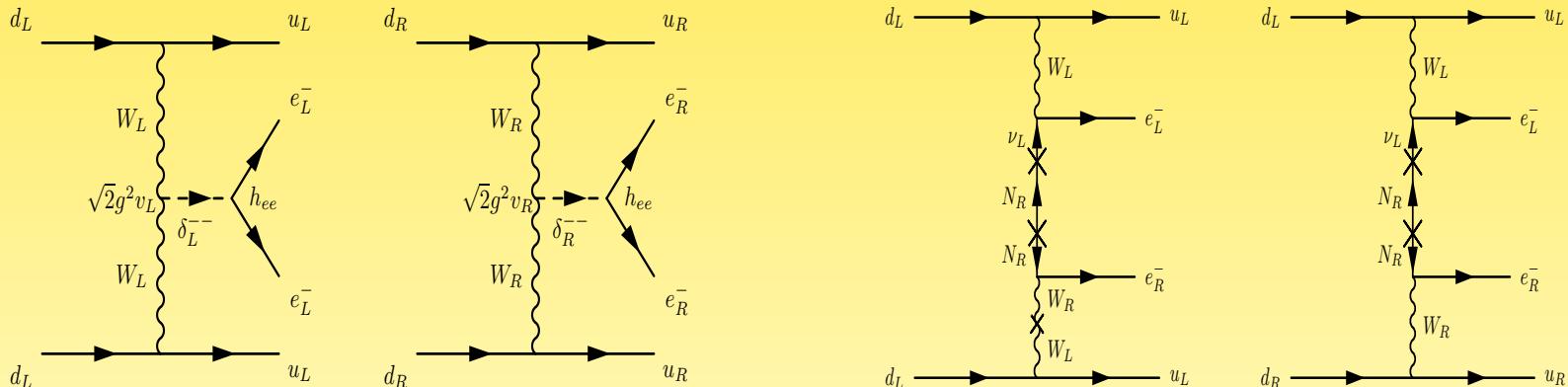
Left-right symmetry



$$U_{ei}^2 m_i$$

$$\frac{S_{ei}^2}{M_i}$$

$$\frac{V_{ei}^2}{M_{W_R}^4 M_i}$$



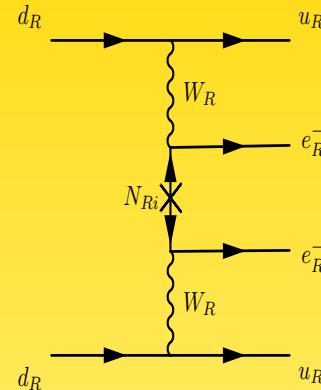
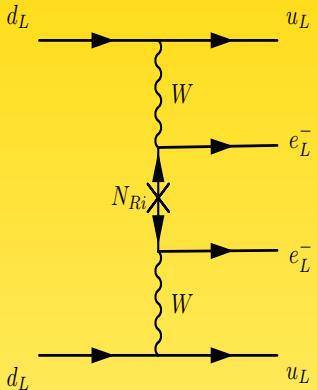
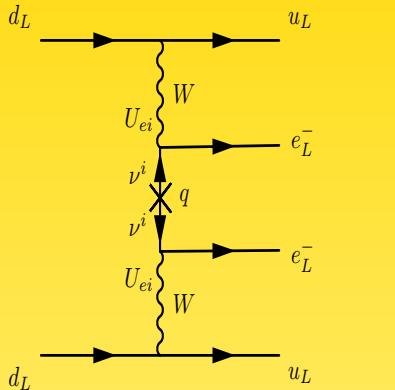
$$\frac{U_{ei}^2 m_i}{M_{\Delta_L}^2}$$

$$\frac{V_{ei}^2 M_i}{M_{W_R}^4 M_{\Delta_R}^2}$$

$$U_{ei} T_{ei} \tan \zeta$$

$$\frac{U_{ei} T_{ei}}{M_{W_R}^2}$$

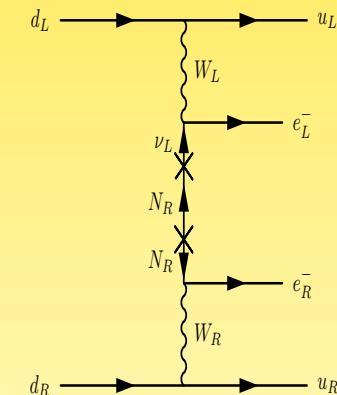
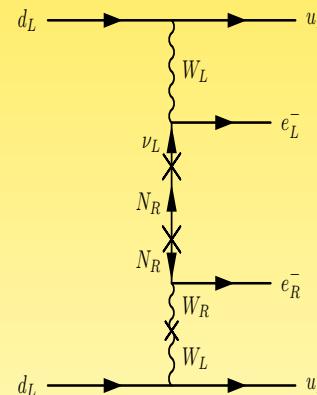
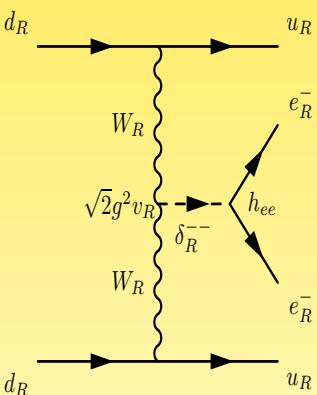
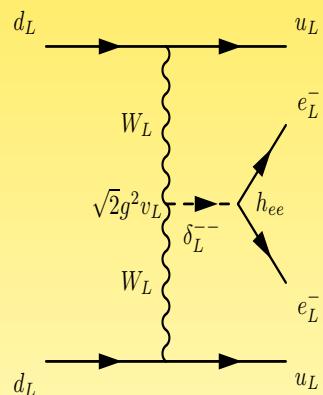
Left-right symmetry



0.4 eV

$2 \times 10^{-8} \text{ GeV}^{-1}$

$4 \times 10^{-16} \text{ GeV}^{-5}$



—

$10^{-15} \text{ GeV}^{-5}$

6×10^{-9}

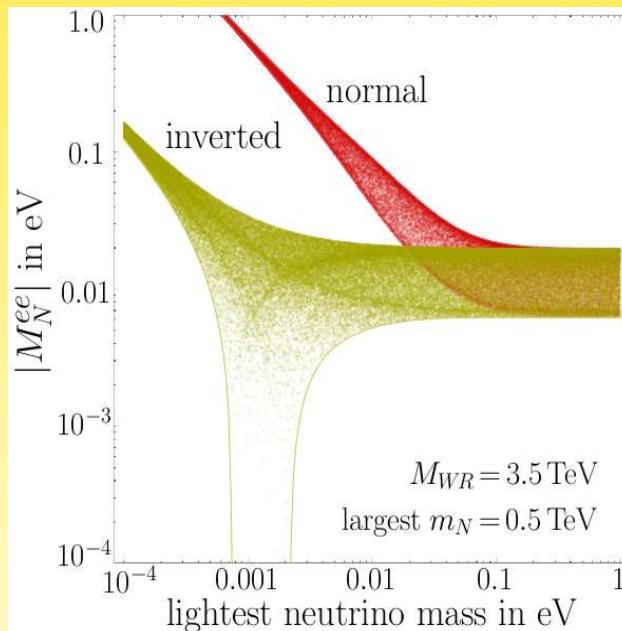
$1.4 \times 10^{-10} \text{ GeV}^{-2}$

Type II dominance ([Tello et al., 1011.3522](#))

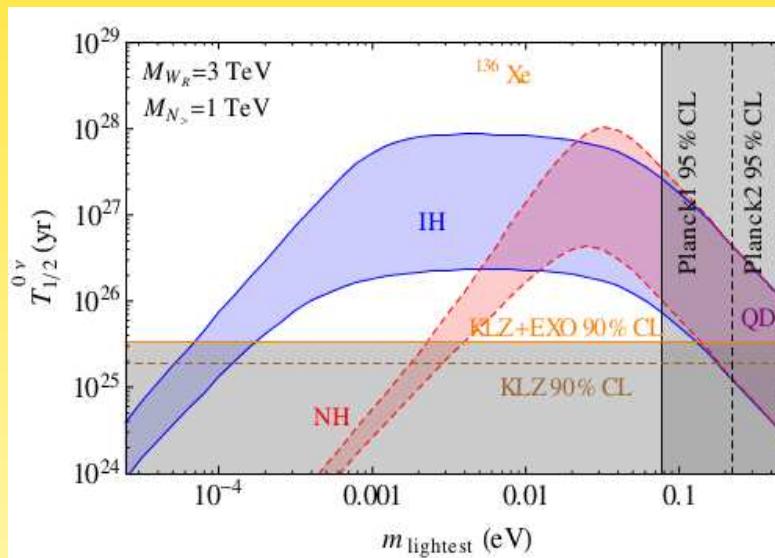
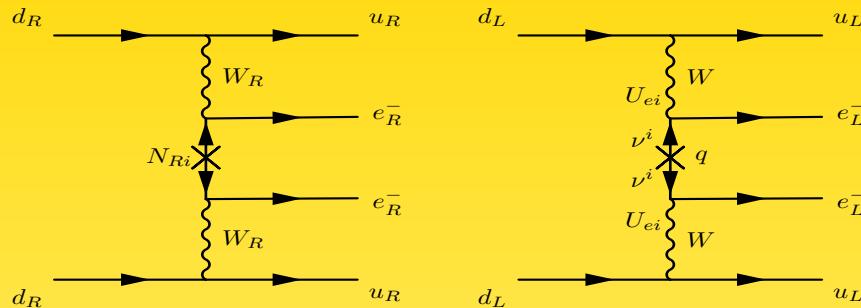
$$m_\nu = m_L - m_D M_R^{-1} m_D^T = v_L f - \frac{v^2}{v_R} Y_D f^{-1} Y_D^T \longrightarrow v_L f$$

m_ν fixes M_R and exchange of N_R with W_R is fixed in terms of PMNS:

$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}} \right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$



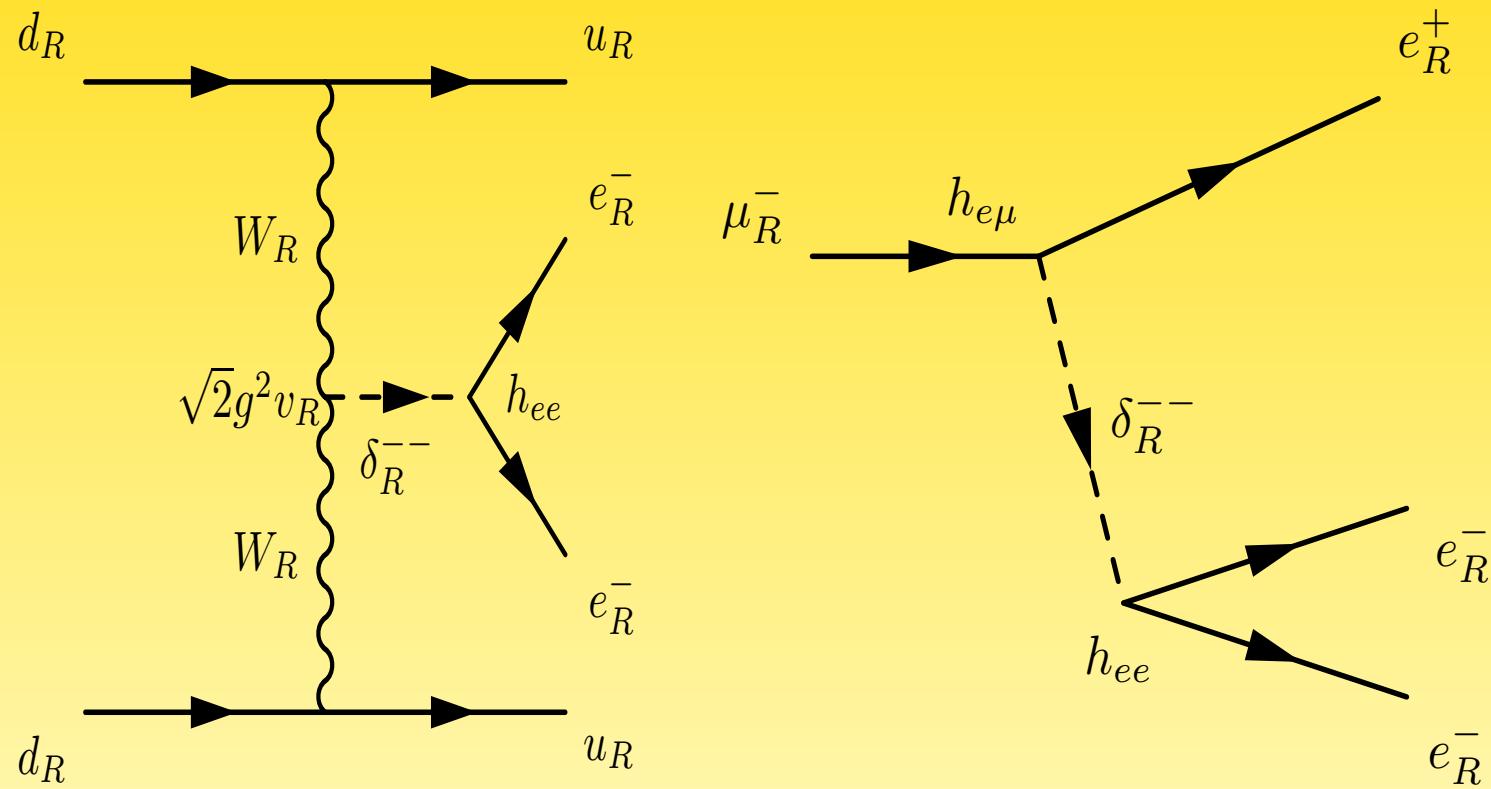
Adding diagrams



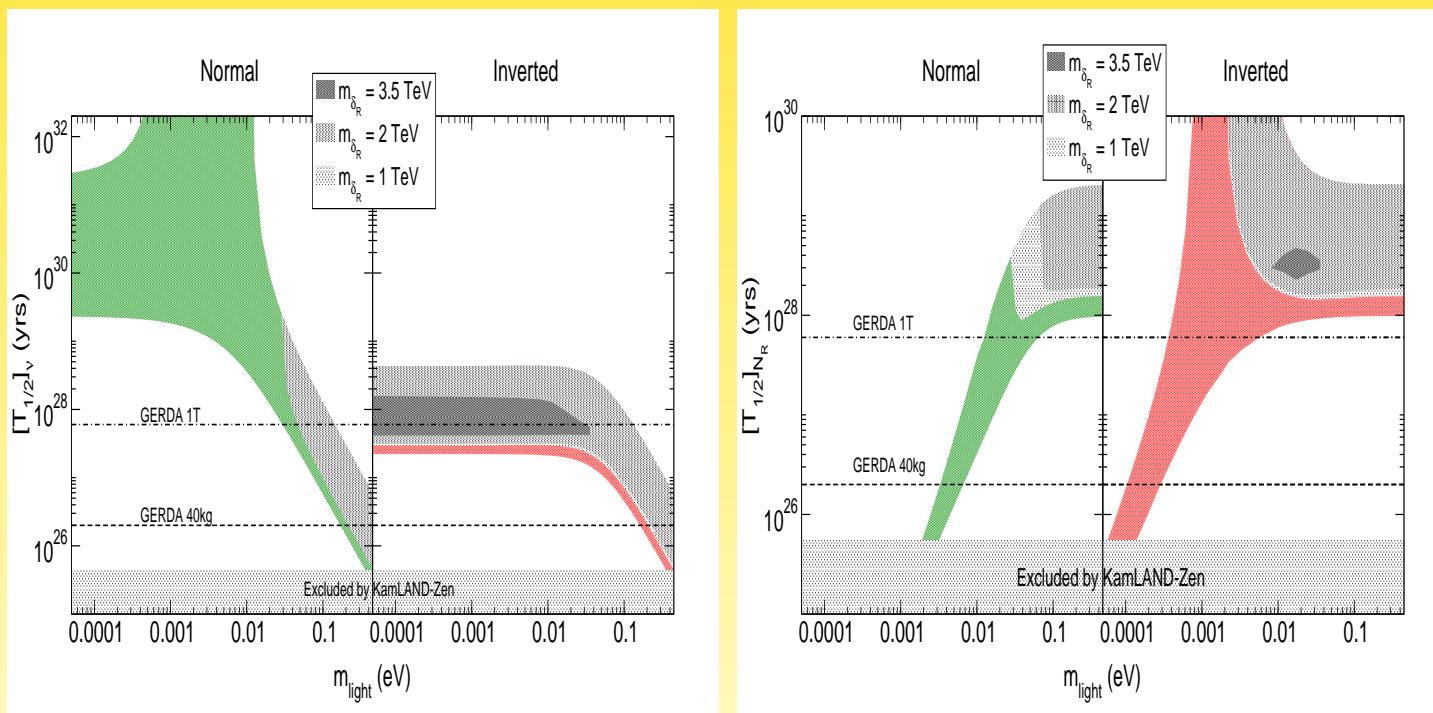
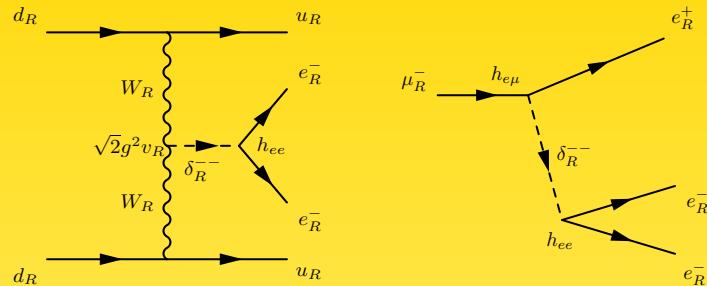
\Rightarrow lower bound on $m(\text{lightest}) \gtrsim \text{meV}$

Bhupal Dev, Goswami, Mitra, W.R., 1305.0056

Constraints from Lepton Flavor Violation

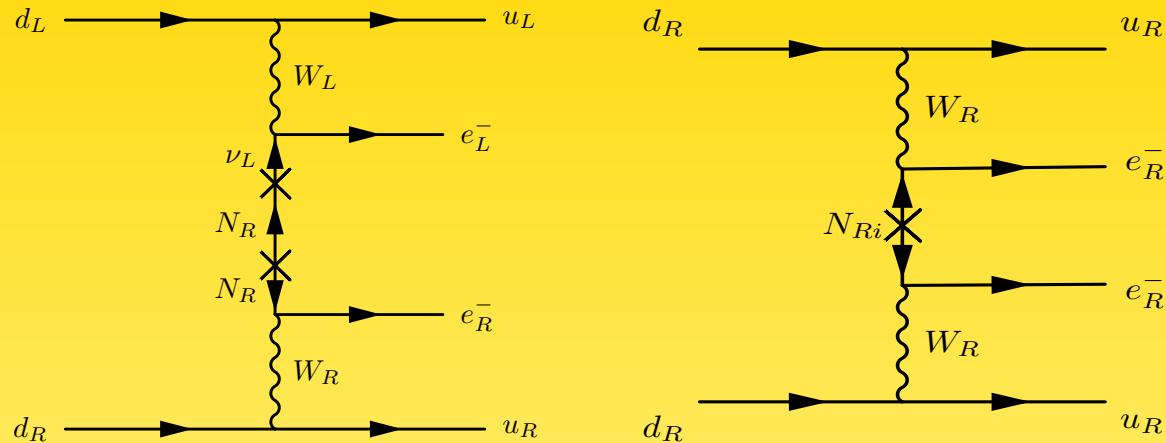


Constraints from Lepton Flavor Violation



Barry, W.R., 1303.6324

Mixed Diagrams can dominate



$$\mathcal{A}_\lambda \sim \left(\frac{m_W}{M_{W_R}} \right)^2 U T \frac{1}{q} \quad \mathcal{A}_{N_R} \sim \left(\frac{m_W}{M_{W_R}} \right)^4 V \frac{1}{M_R}$$

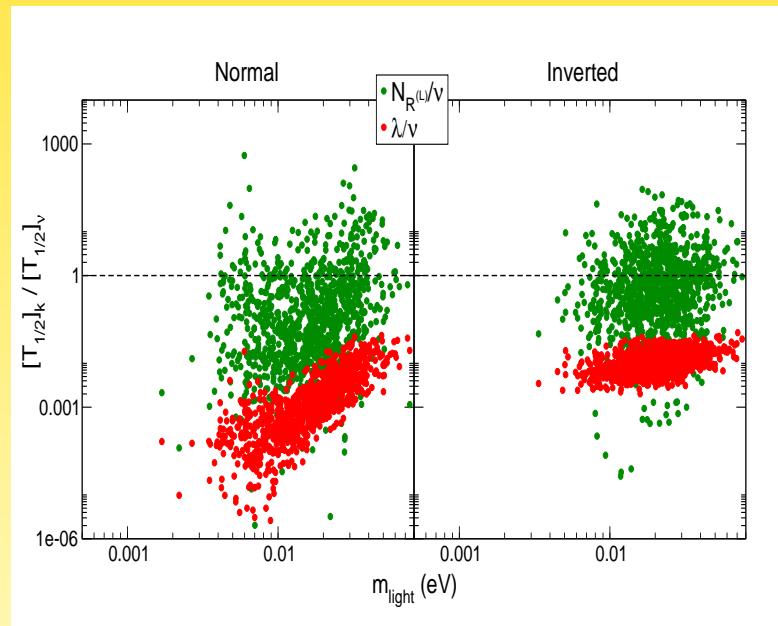
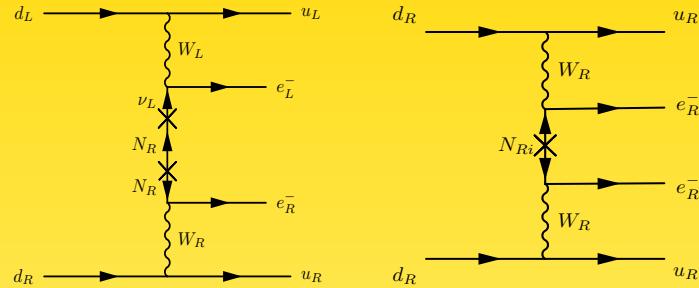
with $T \gtrsim \sqrt{\frac{m_\nu}{M_R}} \sim 10^{-7}$ (or huge enhancements up to 10^{-2})

$$\Rightarrow \frac{\mathcal{A}_{N_R}}{\mathcal{A}_\nu} \simeq \left(\frac{\text{TeV}}{M_{W_R}} \right)^4 \left(\frac{\text{TeV}}{M_R} \right) \left(\frac{0.05 \text{ eV}}{m_\nu} \right)$$

$$\Rightarrow \frac{\mathcal{A}_\lambda}{\mathcal{A}_\nu} \gtrsim \left(\frac{\text{TeV}}{M_{W_R}} \right)^2 \sqrt{\frac{\text{TeV}}{M_R}} \sqrt{\frac{0.05 \text{ eV}}{m_\nu}}$$

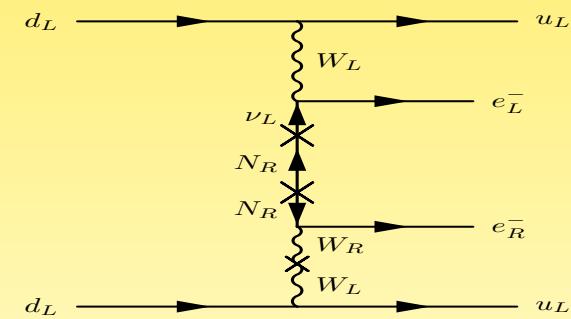
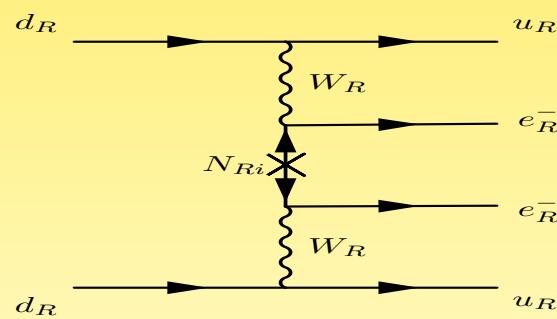
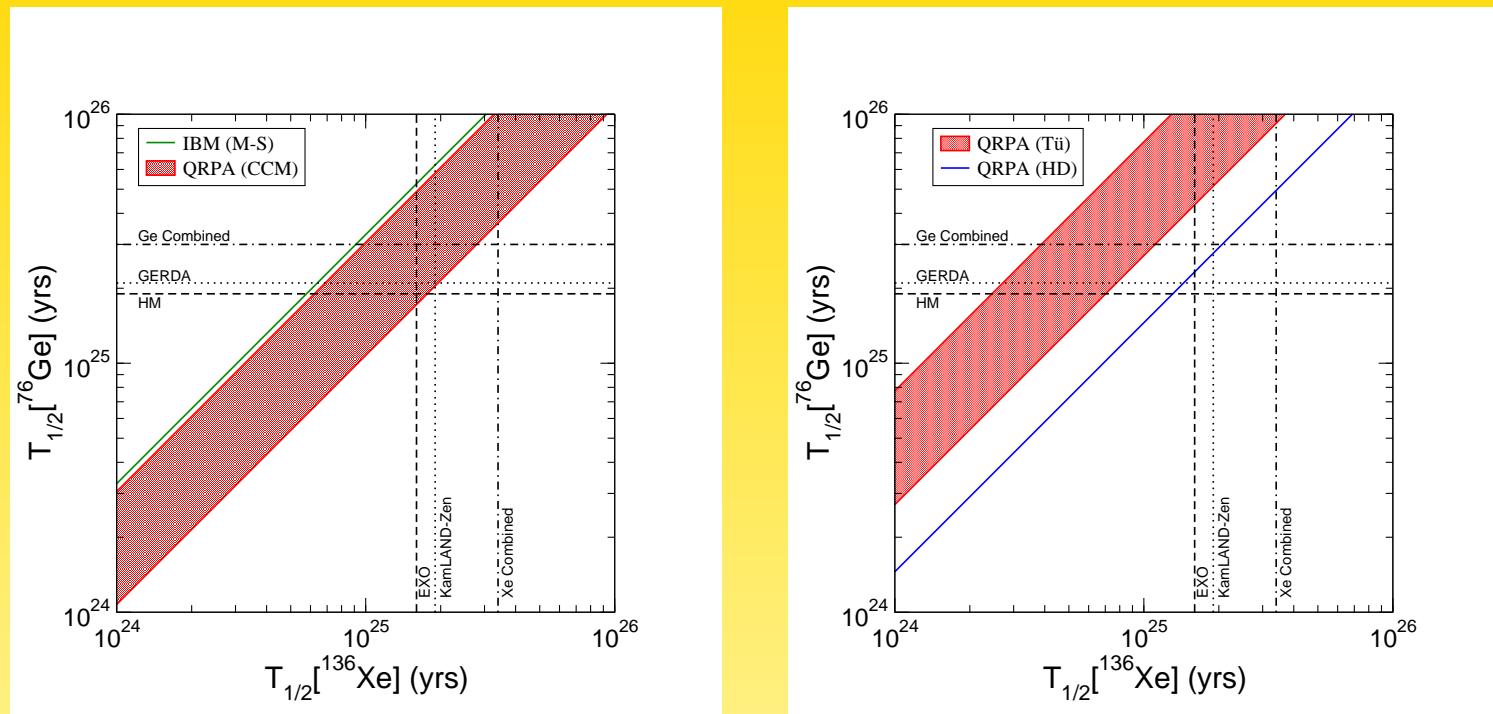
Barry, W.R., 1303.6324

Mixed Diagrams can dominate



Barry, W.R., 1303.6324

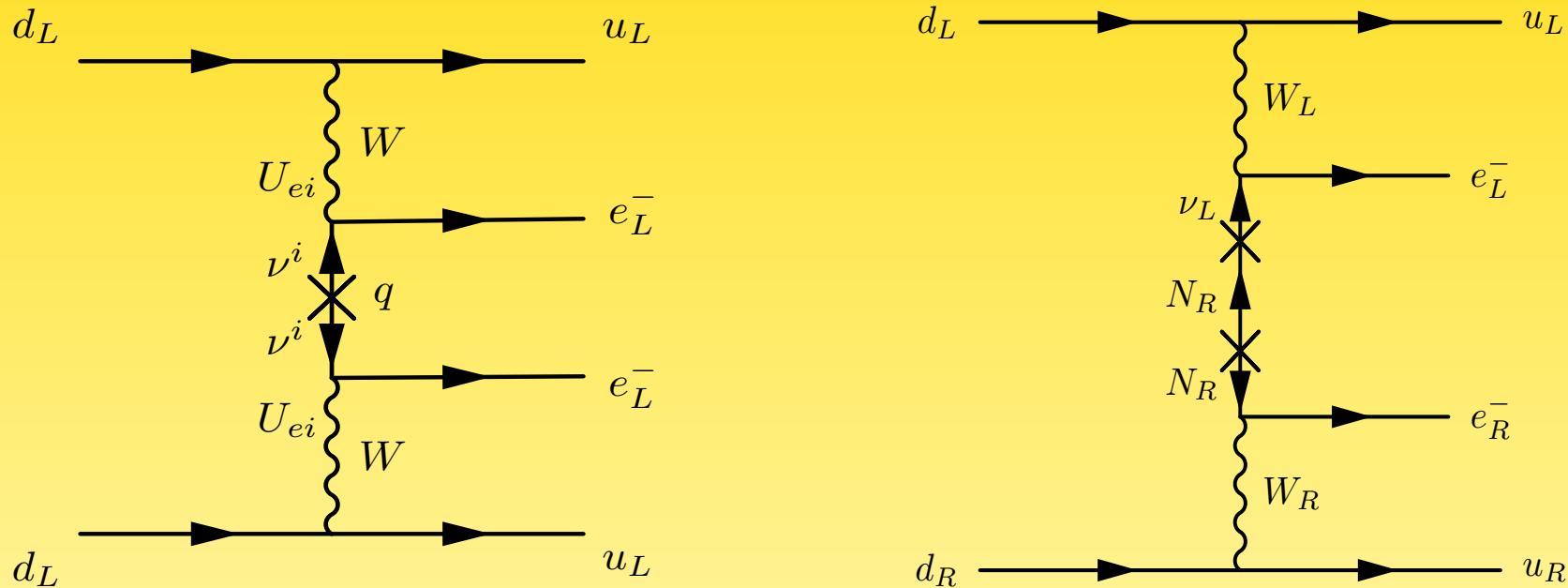
Xe vs. Ge



Barry, W.R., 1303.6324

2.) Distinguishing via decay products

Consider standard plus λ -mechanism



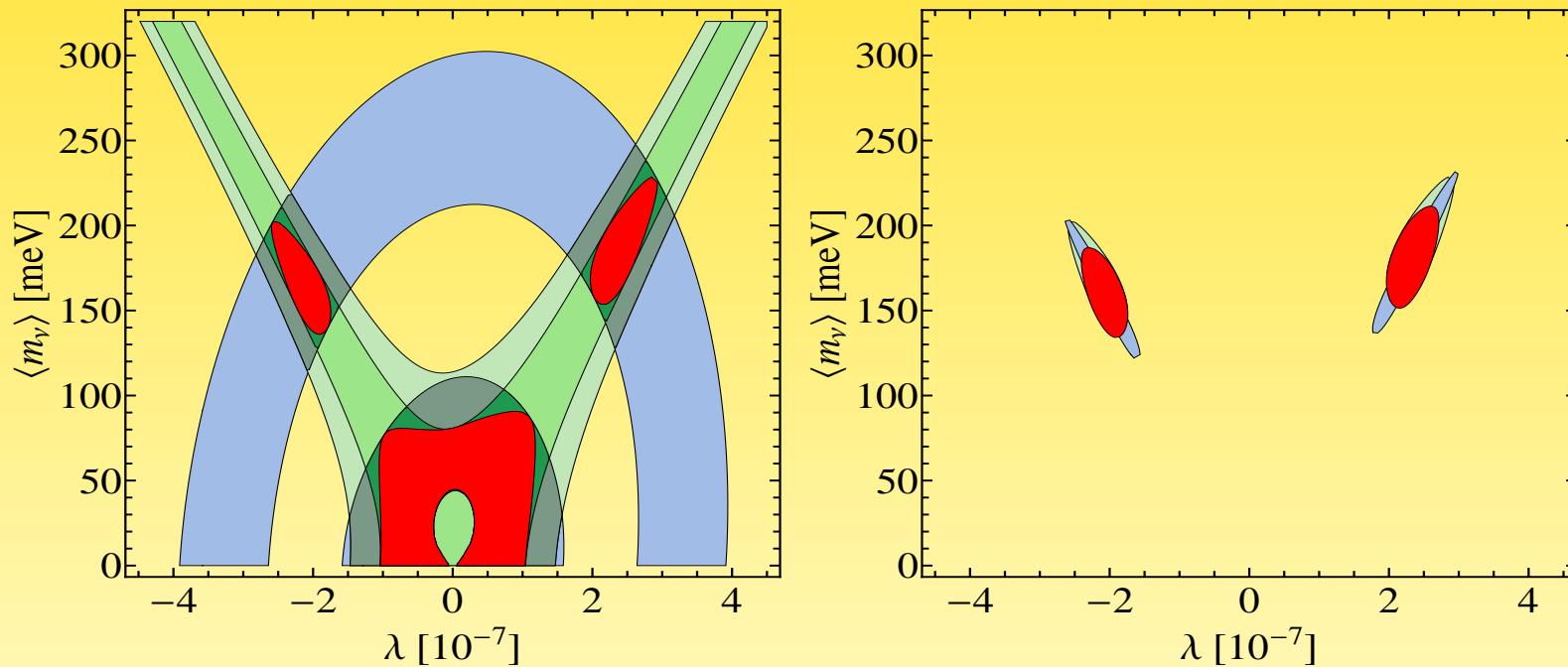
$$\frac{d\Gamma}{dE_1 dE_2 d \cos \theta} \propto (1 - \beta_1 \beta_2 \cos \theta) \quad \frac{d\Gamma}{dE_1 dE_2 d \cos \theta} \propto (E_1 - E_2)^2 (1 + \beta_1 \beta_2 \cos \theta)$$

SuperNEMO, 1005.1241

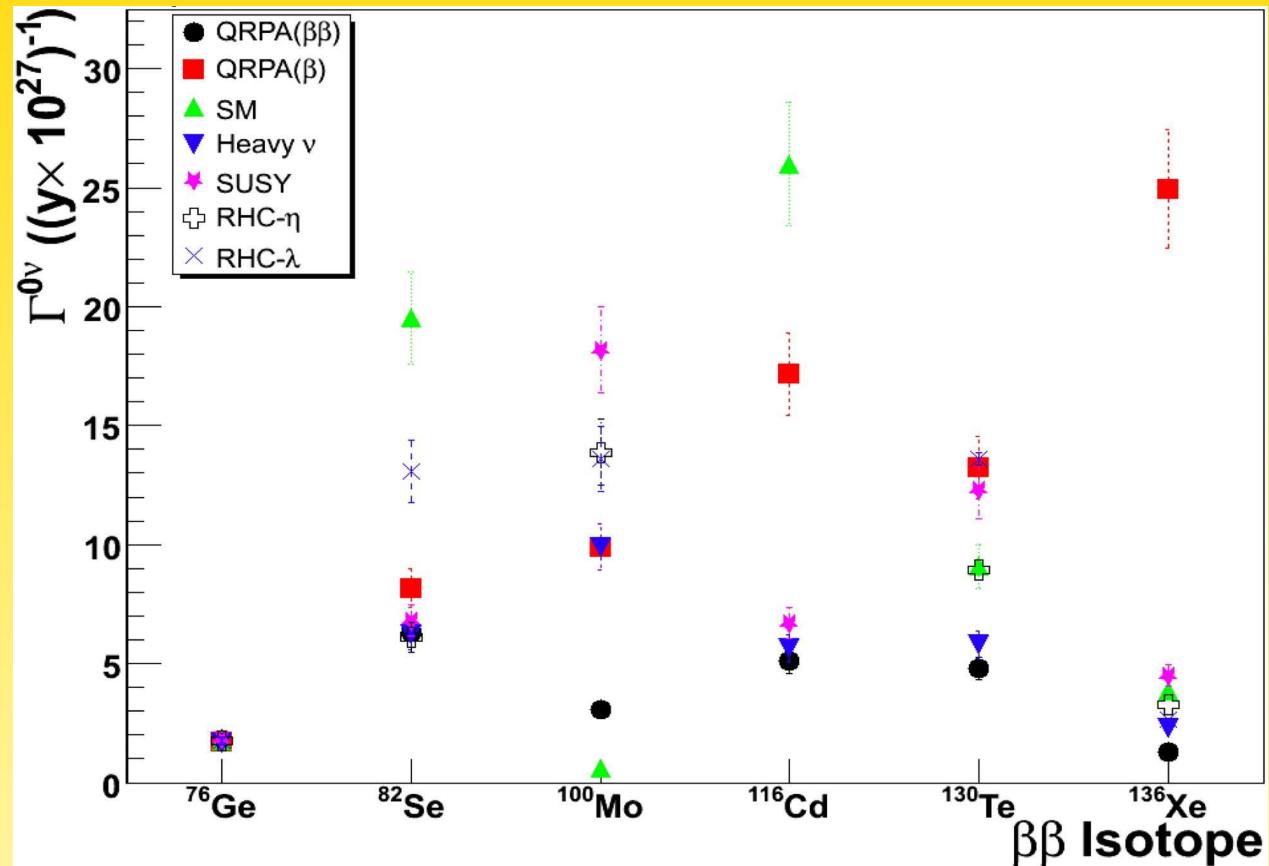
2.) Distinguishing via decay products

Defining asymmetries

$$A_\theta = (N_+ - N_-)/(N_+ + N_-) \text{ and } A_E = (N_> - N_<)/(N_> + N_<)$$



3.) Distinguishing via nuclear physics



Gehman, Elliott, hep-ph/0701099

3 to 4 isotopes necessary to disentangle mechanism

Summary

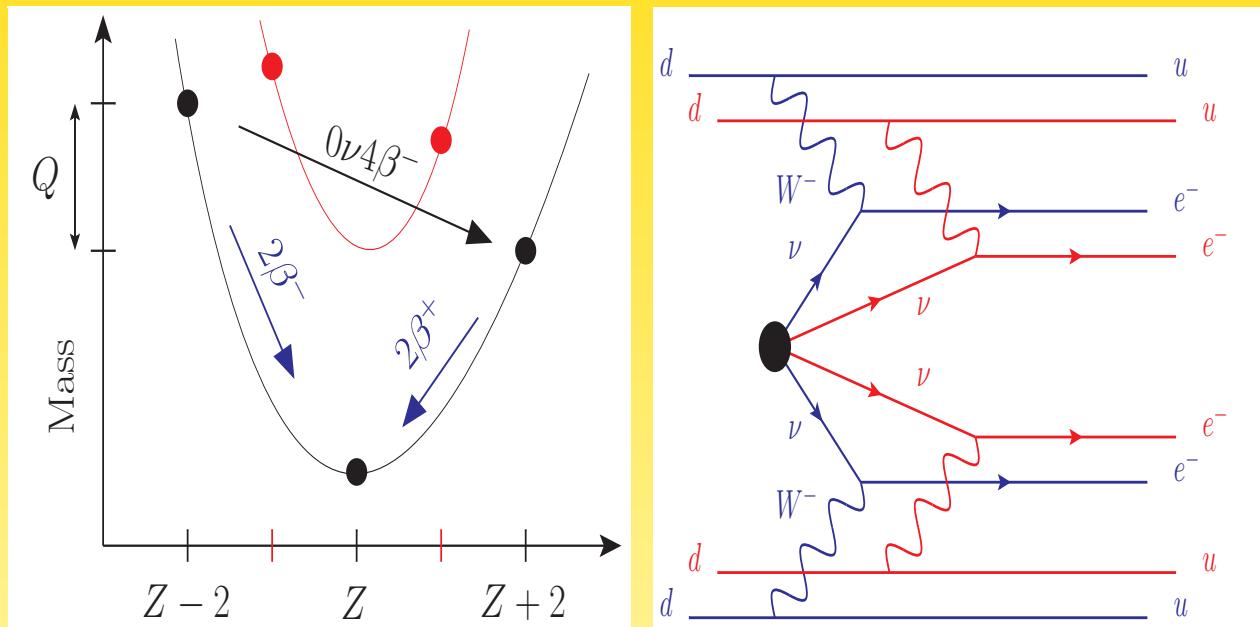
Chi l'ha visto ?



Ettore Majorana ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Maria-
necci, Viale Regina Margherita 66 - Roma.

EXTRA SLIDES FROM HERE ON

Neutrinoless Quadruple Beta Decay



not all $0\nu\beta\beta$ candidates (A, Z) make good $0\nu\beta\beta\beta\beta$ candidates, as $(A, Z + 4)$ can have a larger mass than (A, Z)

Neutrinoless Quadruple Beta Decay

	$Q_{0\nu4\beta}$	Other decays	NA
$^{96}_{40}\text{Zr} \rightarrow ^{96}_{44}\text{Ru}$	0.629	$\tau_{1/2}^{2\nu2\beta} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}\text{Xe} \rightarrow ^{136}_{58}\text{Ce}$	0.044	$\tau_{1/2}^{2\nu2\beta} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}\text{Nd} \rightarrow ^{150}_{64}\text{Gd}$	2.079	$\tau_{1/2}^{2\nu2\beta} \simeq 7 \times 10^{18}$	5.6

daughters are β -stable: $M[^A(Z - 2)] - M[^A(Z + 2)] = 2(M[^A(Z - 1)] - M[^A(Z + 1)])$

Lifetime estimate gives:

$$\frac{\tau_{1/2}^{0\nu4\beta}}{\tau_{1/2}^{2\nu2\beta}} \simeq \left(\frac{Q_{0\nu2\beta}}{Q_{0\nu4\beta}} \right)^{11} \left(\frac{\Lambda^4}{q^{12} G_F^4} \right) \simeq 10^{46} \left(\frac{\Lambda}{\text{TeV}} \right)^4$$

TeV scale seesaw with sizable mixing

Simple example:

$$M_D = m \begin{pmatrix} f\epsilon^2 & 0 & 0 \\ 0 & g\epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad M_R^{-1} = M^{-1} \begin{pmatrix} a & b & k \\ b & c & d\epsilon \\ k & d\epsilon & e\epsilon^2 \end{pmatrix}$$

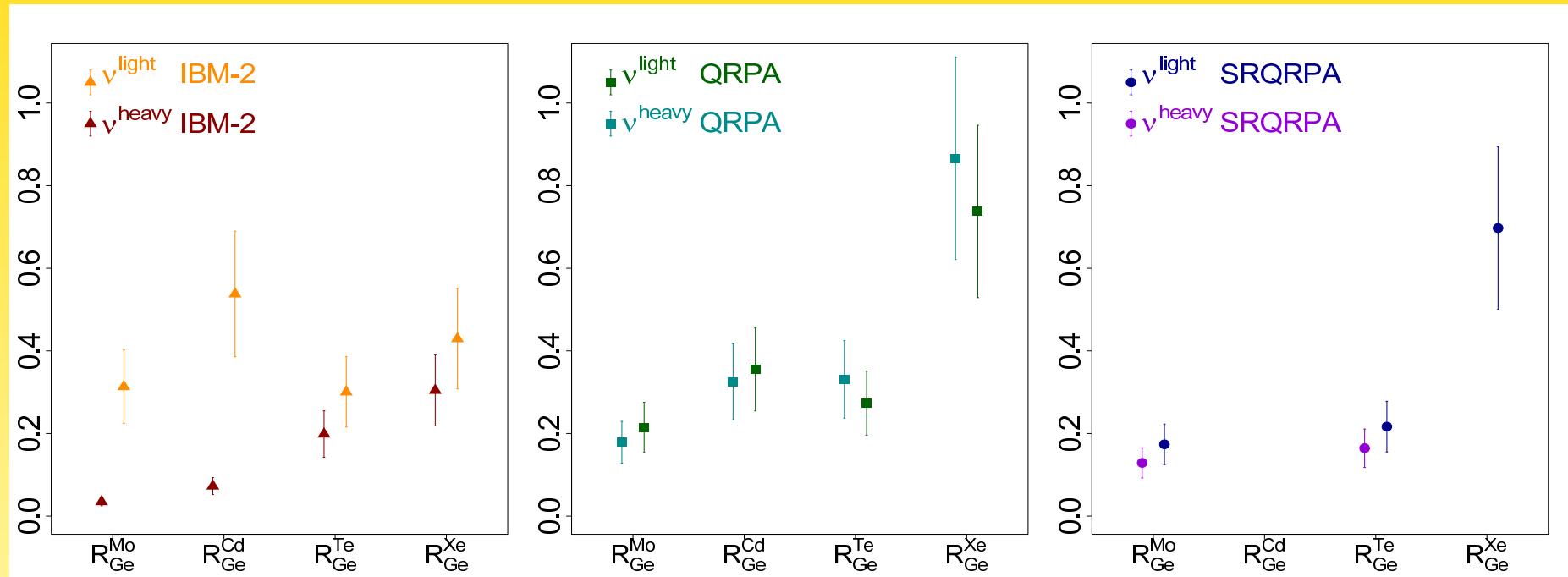
M/GeV	m/MeV	ϵ	a	k	b	c	d	e	f	g
5.00	0.935	0.02	1.00	1.35	0.90	1.4576	0.7942	0.2898	0.0948	0.485

gives successful m_ν and

$$\left| \frac{\mathcal{A}_l}{\mathcal{A}_h} \right| \simeq 10^{-2}$$

Mitra, Senjanovic, Vissani, NPB **856**

3.) Distinguishing via nuclear physics?

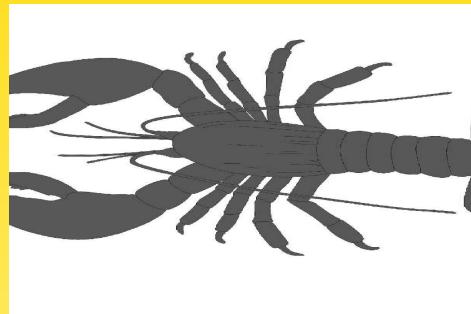
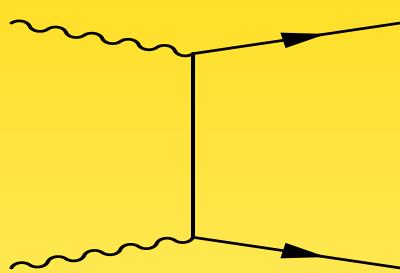


Lifetime ratios with respect to Ge

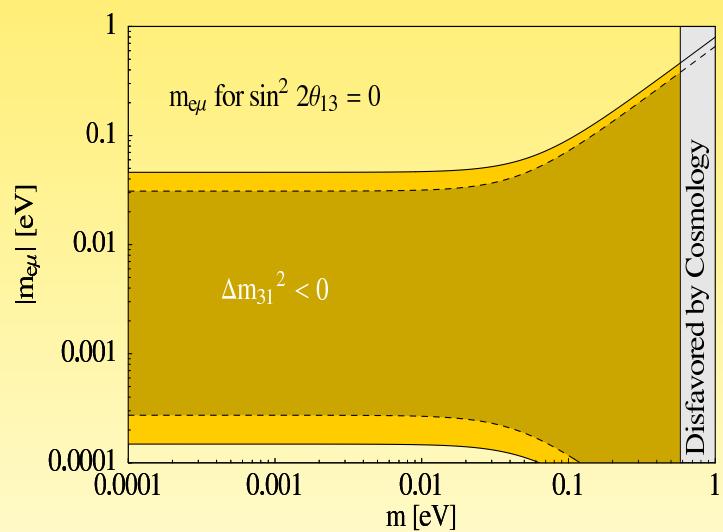
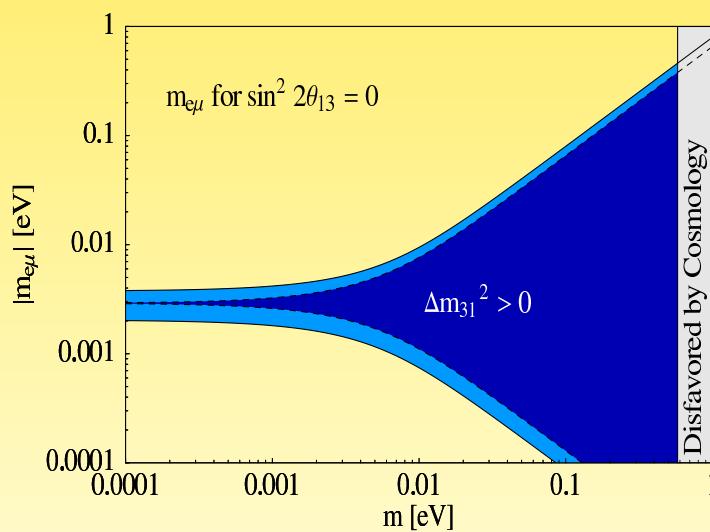
Bleher, W.R., in preparation

Alternative processes?

The lobster:



$$\text{BR}(K^+ \rightarrow \pi^- e^+ \mu^+) \propto |m_{e\mu}|^2 = \left| \sum U_{ei} U_{\mu i} m_i \right|^2 \sim 10^{-30} \left(\frac{|m_{e\mu}|}{\text{eV}} \right)^2$$



2 kinds of neutrino masses

1) ee -element of mass matrix: $m_{ee} = (m_\nu)_{ee}$

$$\sqrt{\frac{1}{T_{1/2}^{0\nu}}} \propto |(m_\nu)_{ee}| \quad \text{with } (m_\nu)_{ee} = \frac{h_{ee} v^2}{\Lambda} \quad \text{in } \mathcal{L}_{\text{eff}} = \frac{1}{2} \frac{h_{\alpha\beta}}{\Lambda} \overline{L}_\alpha^c \tilde{\Phi} \tilde{\Phi}^T L_\beta$$

fundamental object in low energy Lagrangian!

2) neutrino mass scale: QD neutrinos

$$|m_{ee}|^{\text{QD}} = m_0 \left| c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{2i\alpha} + s_{13}^2 e^{2i\beta} \right|$$
$$\Rightarrow m_0 \leq |m_{ee}|_{\min}^{\text{exp}} \frac{1 + \tan^2 \theta_{12}}{1 - \tan^2 \theta_{12} - 2 |U_{e3}|^2} \leq \begin{cases} 1.0 \text{ eV} & (1\sigma) \\ 1.4 \text{ eV} & (3\sigma) \end{cases}$$

same order as Mainz/Troitsk!

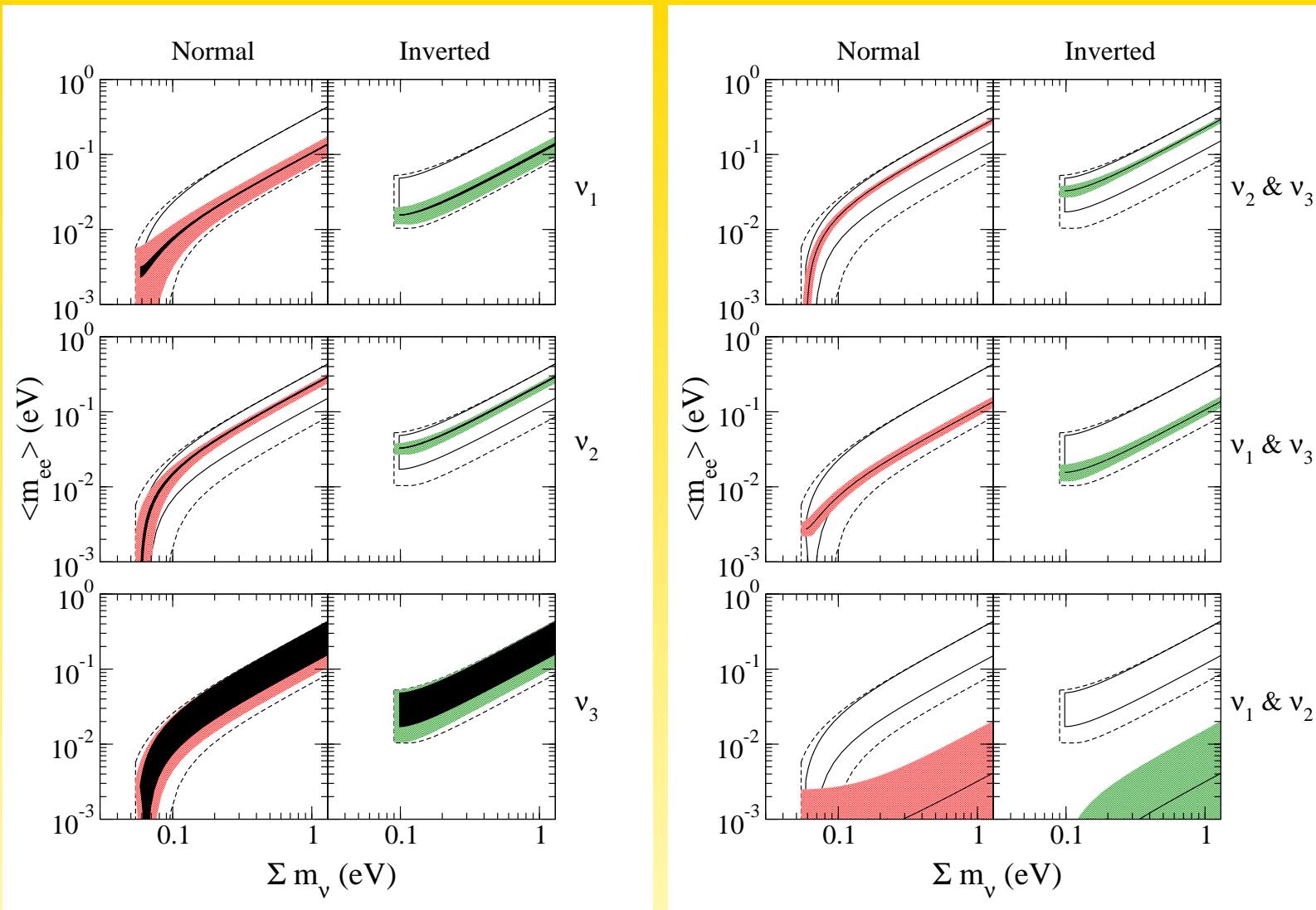
Exotic modifications of the neutrino picture

- Dirac neutrinos
- Pseudo-Dirac neutrinos: for each mass state

$$m_i \begin{pmatrix} \epsilon & 1 \\ 1 & 0 \end{pmatrix} \rightarrow U = \sqrt{\frac{1}{2}} \begin{pmatrix} 1 + \frac{\epsilon}{4} & -1 + \frac{\epsilon}{4} \\ 1 - \frac{\epsilon}{4} & 1 + \frac{\epsilon}{4} \end{pmatrix} \text{ and } m_i^\pm = m_i \left(\pm 1 + \frac{\epsilon}{2} \right)$$

and $|m_{ee}|^{(i)} = \epsilon m_i = \frac{1}{2} \delta m^2 / m_i$, with $\delta m^2 = (m_i^+)^2 - (m_i^-)^2$

- one neutrino could be (Pseudo-)Dirac, the other Majorana!
“Schizophrenic neutrinos”



Mohapatra *et al.*, 1008.1232; Barry, Mohapatra, W.R., 1012.1761

Exotic exotics

- 1) CPT violation: introduce violation of CPT and L: not really “Majorana neutrinos”, but $0\nu\beta\beta$ still possible

Barenboim, Beacom, Borissov, Kayser

- 2) tachyonic neutrinos: “Dirac” equation does not allow to have charge conjugation, “no $0\nu\beta\beta$ possible”

Chodos, Hauser, Kostelecky; Jentschura

Leptogenesis

- distribute conserved lepton number $\Delta L = 0$ in left- and right-handed sectors
 $\Delta L_L \neq 0, \Delta L_R = -\Delta L_L$
- sphalerons only work on left-handed particles
- sphalerons transform ΔL_L into $\Delta B \neq 0$

Dick *et al.*, PRL84

“Inverse $0\nu\beta\beta$ ”

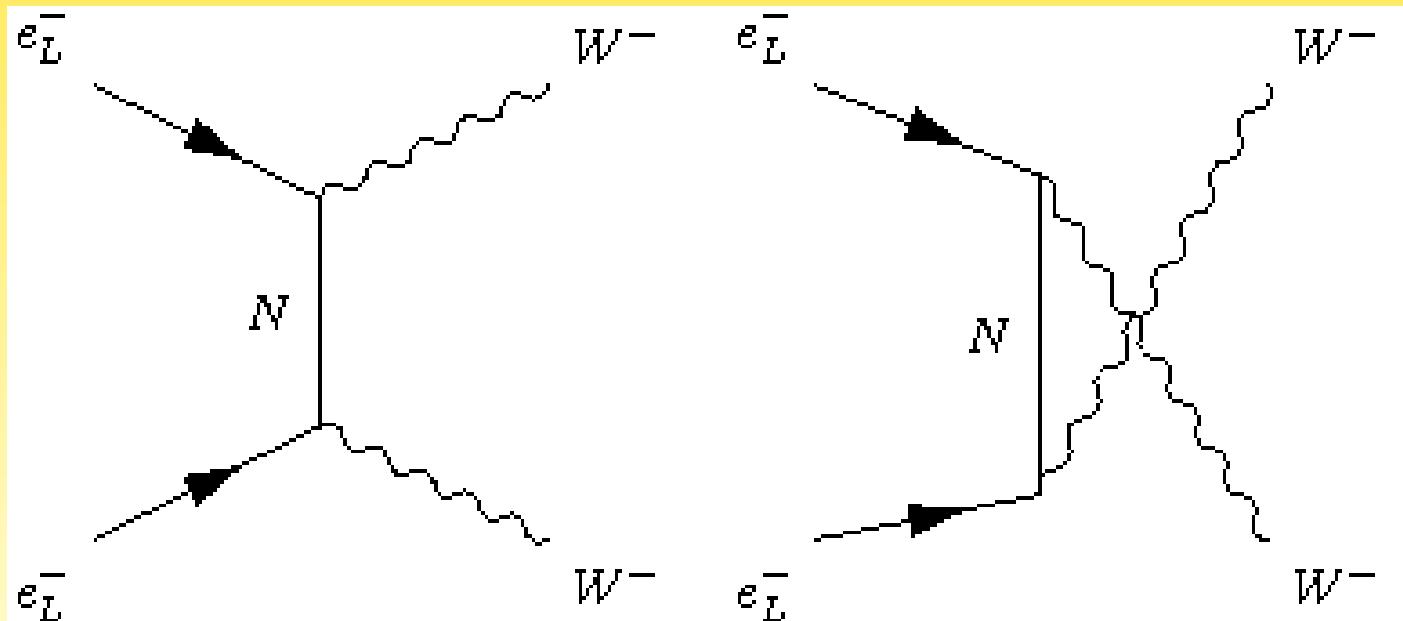
this is not



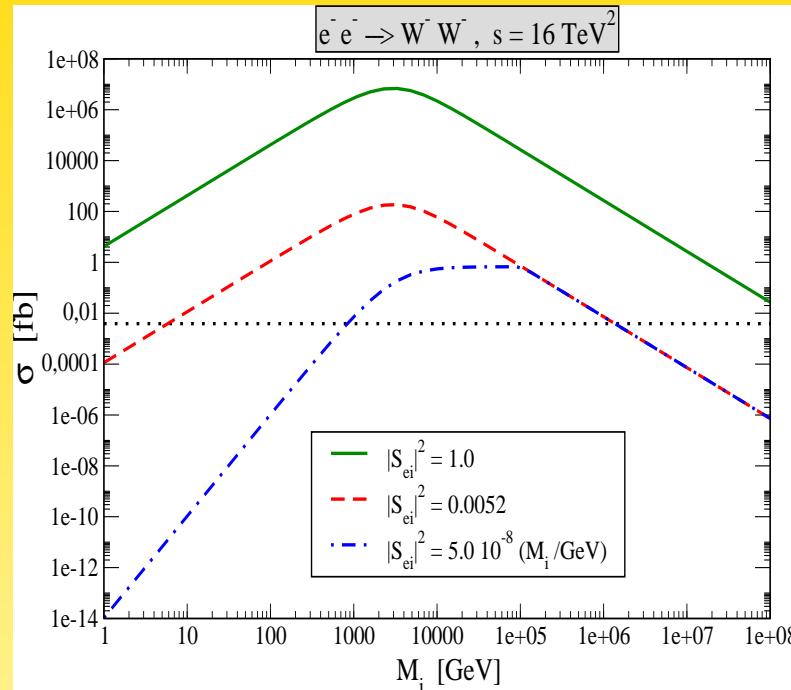
but rather



Rizzo; Heusch, Minkowski; Gluza, Zralek; Cuypers, Raidal;...



Inverse Neutrinoless Double Beta Decay



W.R., PRD **81**

$$\frac{d\sigma}{d \cos \theta} = \frac{G_F^2}{32 \pi} \left\{ \sum (m_\nu)_i \mathcal{U}_{ei}^2 \left(\frac{t}{t - (m_\nu)_i} + \frac{u}{u - (m_\nu)_i} \right) \right\}^2$$

Inverse Neutrinoless Double Beta Decay

Extreme limits:

- light neutrinos:

$$\sigma(e^- e^- \rightarrow W^- W^-) = \frac{G_F^2}{4\pi} |m_{ee}|^2 \leq 4.2 \cdot 10^{-18} \left(\frac{|m_{ee}|}{1 \text{ eV}} \right)^2 \text{ fb}$$

⇒ way too small

- heavy neutrinos:

$$\sigma(e^- e^- \rightarrow W^- W^-) = 2.6 \cdot 10^{-3} \left(\frac{\sqrt{s}}{\text{TeV}} \right)^4 \left(\frac{S_{ei}^2/M_i}{5 \cdot 10^{-8} \text{ GeV}^{-1}} \right)^2 \text{ fb}$$

⇒ too small

- $\sqrt{s} \rightarrow \infty$:

$$\sigma(e^- e^- \rightarrow W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2 (m_\nu)_i \right)^2$$

⇒ amplitude grows with \sqrt{s} ? Unitarity??

Unitarity

high energy limit $\sqrt{s} \rightarrow \infty$:

$$\sigma(e^- e^- \rightarrow W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2 (m_\nu)_i \right)^2$$

\leftrightarrow amplitude grows with \sqrt{s} ?

Answer: exact see-saw relation $\mathcal{U}_{ei}^2 (m_\nu)_i = 0$

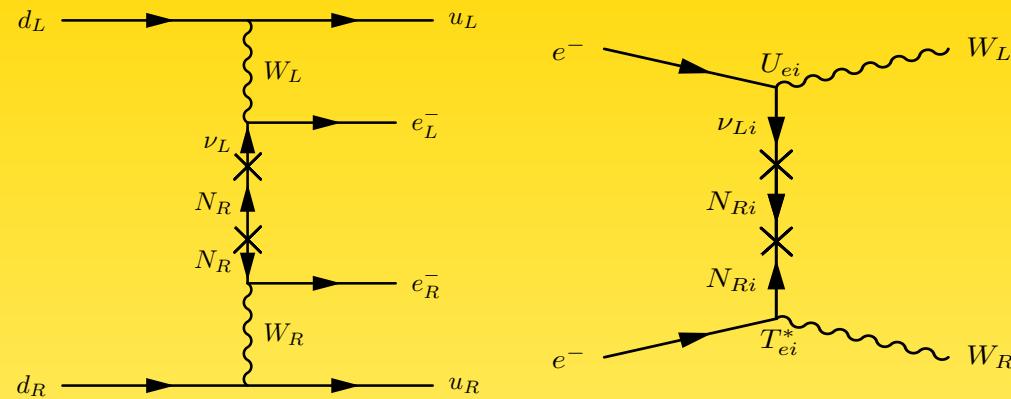
$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \mathcal{U} \begin{pmatrix} m_\nu^{\text{diag}} & 0 \\ 0 & M_R^{\text{diag}} \end{pmatrix} \mathcal{U}^T$$

if Higgs triplet is present: unitarity also conserved

$$\sigma(e^- e^- \rightarrow W^- W^-) = \frac{G_F^2}{4\pi} \left((\mathcal{U}_{ei}^2 (m_\nu)_i - (m_L)_{ee})^2 \right) = 0$$

W.R., PRD **81**

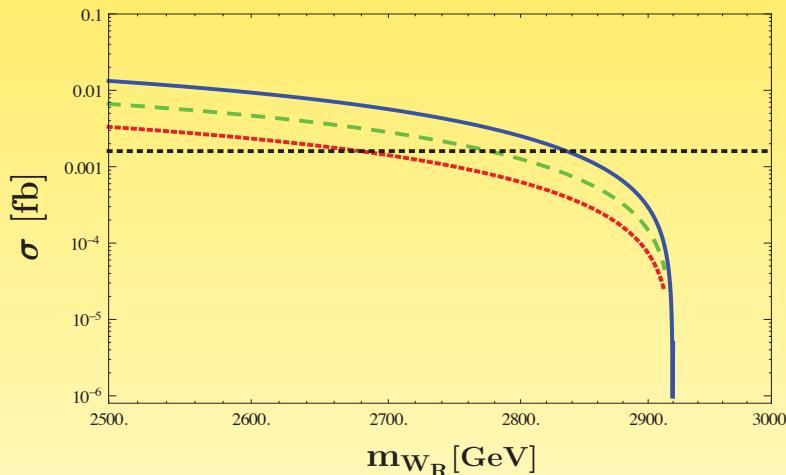
First possibility: λ -diagram in LR symmetry



$0\nu\beta\beta$

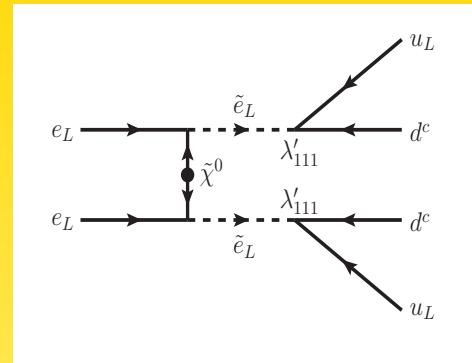
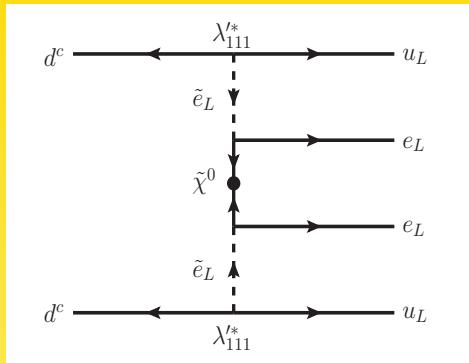
$W-W_R$ production

$$e^- e^- \rightarrow W_L^- W_R^-, s = 9 \text{ TeV}^2$$



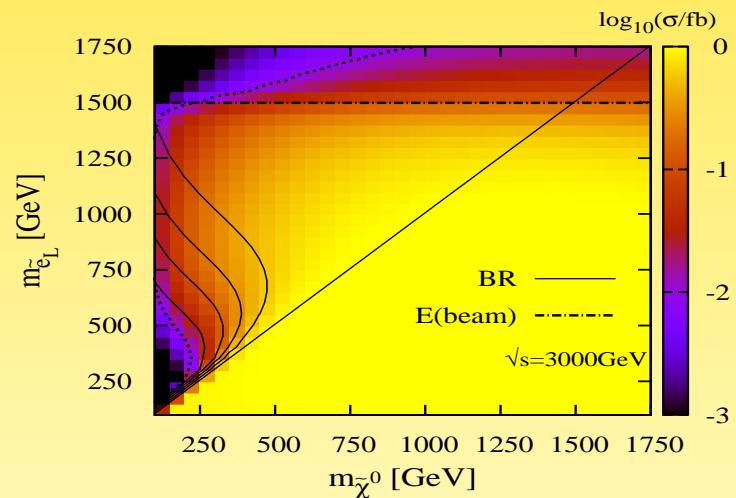
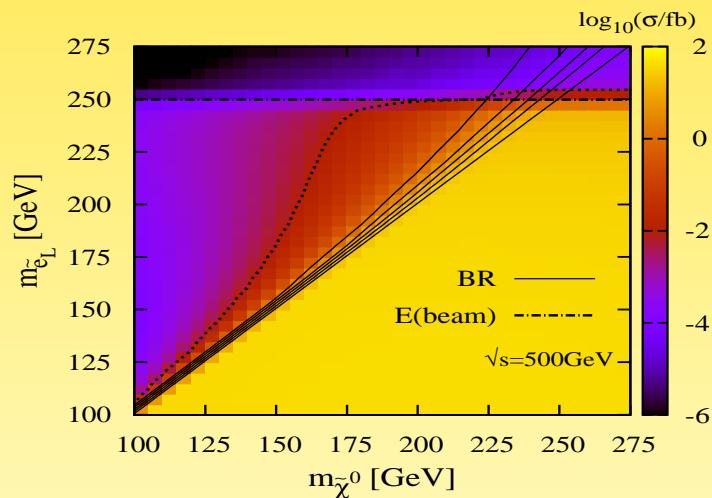
Barry, Dorame, W.R., 1204.3365

Second possibility: RPV SUSY



$0\nu\beta\beta$

resonant \tilde{e}_L production $\rightarrow 4j$

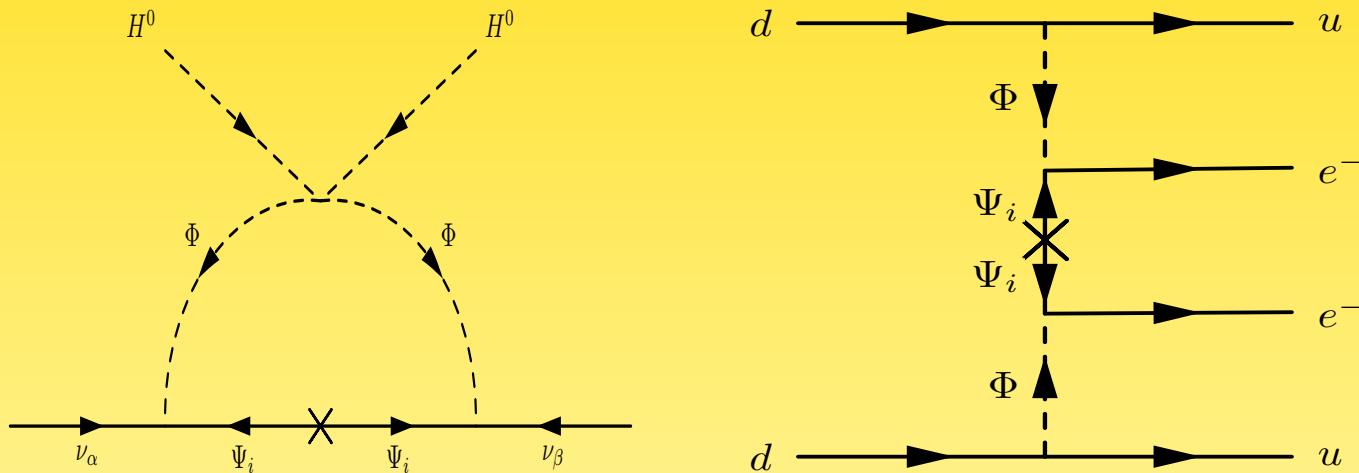


Kom, W.R., 1110.3220

Direct vs. Indirect Contribution

Example: Color Octet Mechanism (Perez, Wise, PRD 80)

introduce $\psi_i = (8, 1, 0)$ and $\Phi = (8, 2, \frac{1}{2})$

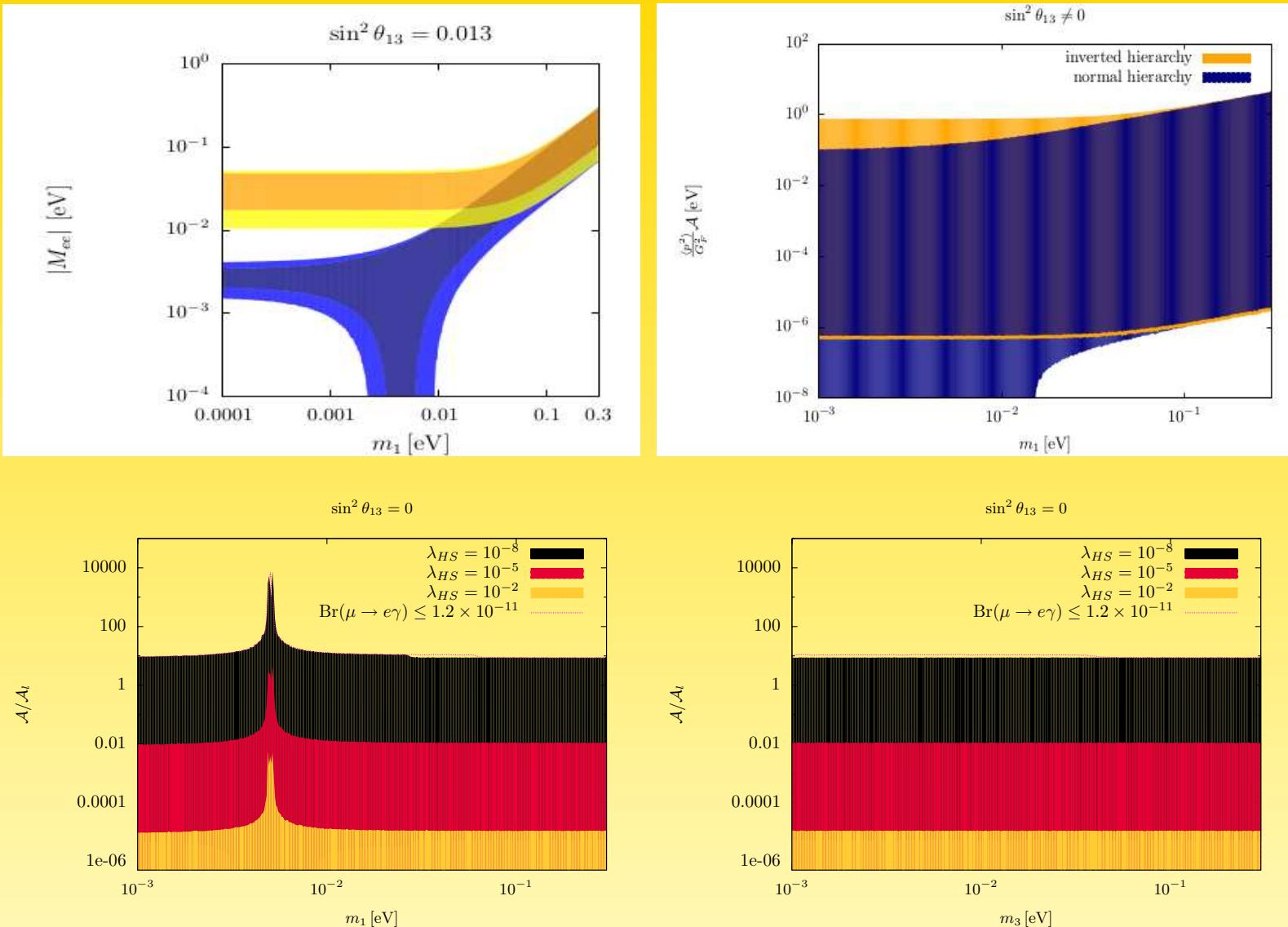


1-loop m_ν

indirect contribution to $0\nu\beta\beta$: direct contribution to $0\nu\beta\beta$:

$$\mathcal{A}_l \simeq G_F^2 \frac{|m_{ee}|}{q^2}$$

$$\mathcal{A} \simeq c_{ud}^2 \frac{y_{e\alpha}^2}{M_{\psi_i} M_\Phi^4}$$



Choubey, Dürr, Mitra, W.R., 1201.3031